Agent-Based Modeling of Flexible Access – User Behavior and Satisfaction

Joonas Lindh

School of Electrical Engineering

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Thesis supervisor:

Prof. Heikki Hämmäinen

Thesis advisor:

Docent Kalevi Kilkki

Aalto University
School of Electrical Engineering

AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

ABSTRACT OF THE
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Author: Joonas Lindh

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Supervisor: Prof. Heikki Hämmäinen

Advisor: Docent Kalevi Kilkki

While mobile networks continuously reach more of the population with better technology, there are always disparities between operators in coverage and capacity. This thesis studies flexible access – the use of all available access networks when needed – and how it could improve the satisfaction of mobile end users with their service. Two mechanisms for flexible access, end-user multihoming and national roaming, are studied by examining literature and by performing expert interviews.

Agent-based modeling is a method to study phenomena which naturally comprise of individual actors, called agents. In this thesis, an agent-based model of mobile user behavior is created to study and compare user satisfaction between single access and flexible access. Mobile users and base stations are placed on a two-dimensional map and their behavior is implemented with computer simulation.

The results of the agent-based modeling experiments suggest that the satisfaction of users increases with flexible access when the coverage disparity between networks increases, compared with single access. The method is suitable for studying mobile usage scenarios, but the model assumptions need to be more rigorously defined. The resulting computer simulation model can be used as a platform for future modeling. The literature and interviews show that flexible access mechanisms can improve network availability and throughput for users. However, many factors affect the adoption of national roaming and end-user multihoming.

Keywords: agent-based modeling, flexible access, user satisfaction, end-user multihoming, national roaming

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Vaikka mobiiliverkot kattavat jatkuvasti suuremman osan väestöstä ja tarjoavat parempaa tekniikkaa, verkko-operaattorien välillä on aina eroja peitossa ja kapasiteetissa. Tämä diplomityö tutkii joustavaa pääsyä, eli usean saatavilla olevan liityntäverkon käyttöä tarpeen mukaan, ja kuinka se voisi lisätä mobiiliverkon loppukäyttäjien tyytyväisyyttä palveluun. Kirjallisuuden ja haastatteluiden avulla tarkastellaan loppukäyttäjän moniyhteyttä ja kansallista verkkovierailua, jotka ovat mekanismeja toteuttaa joustava pääsy.

Agenttipohjaisen mallinnuksen avulla voidaan tutkia ilmiöitä, jotka koostuvat luonnollisesti itsenäisistä toimijoista, agenteista. Tässä diplomityössä luodaan agenttipohjainen malli mobiilikäyttäjien toiminnasta ja verrataan käyttäjätyytyväisyyttä yhden verkon käytön ja joustavan pääsyn välillä. Käyttäjät ja tukiasemat sijoitetaan kaksiulotteiselle kartalle ja niiden toiminta toteutetaan tietokonesimulaation avulla.

Agenttipohjaisten kokeiden perusteella joustava pääsy näyttää lisäävän käyttäjätyytyväisyyttä verrattuna vain yhden verkon käyttöön, kun operaattorien peittoerot kasvavat. Agenttipohjainen mallinnus metodina sopii mobiiliverkkojen käyttötilanteiden tutkimiseen, mutta mallintamisessa tehtävät oletukset on määriteltävä tarkoin ja perustellusti. Työn tuloksena luotua simulaatiomallia voidaan käyttää pohjana tulevalle tutkimukselle. Kirjallisuuden ja haastattelujen perusteella joustavan pääsyn mekanismit voivat lisätä verkon saatavuutta ja palvelun nopeutta. Monet tekijät kuitenkin vaikuttavat siihen, kannattaako kansallinen verkkovierailu tai loppukäyttäjän moniyhteys ottaa käyttöön.

Avainsanat: agenttipohjainen mallinnus, joustava pääsy, käyttäjätyytyväisyys, loppukäyttäjän moniyhteys, kansallinen verkkovierailu

Preface

This Master's Thesis has been written as a partial fulfilment for the degree of Master of Science in Technology, in the Department of Communications and Networking at the Aalto University School of Electrical Engineering. The study was carried out as a part of the Emergent project.

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Finally, I want to thank my girlfriend, Hilla, for her love and support.

Otaniemi, 6.10.2016

Joonas Lindh

Contents

Abbreviations

2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	3^{rd} Generation Partnership Project
4G	4^{th} Generation
ABM	Agent-Based Modeling
BS	Base Station
ENISA	European Union Agency for Network and Information Security
eSIM	Embedded Subscriber Identity Module
GSM	Global System for Mobile Communications
GSMA	GSM Association
HIP	Host Identity Protocol
IDE	Integrated Development Environment
IP	Internet Protocol
M2M	Machine-to-Machine
MIP	Mobile IP
MNO	Mobile Network Operator
MO-MVNO	Multi-Operator Mobile Virtual Network Operator
MPTCP	Multipath TCP
MVNO	Mobile Virtual Network Operator
NR	National Roaming
QoS	Quality of Service
SIM	Subscriber Identity Module
TCP	Transmission Control Protocol

1 Introduction

Mobile Internet usage is growing steadily. In Finland, 69 % of the population use a smartphone (OSF, 2015). The increased usability of mobile devices and the versatility of online services results in continuous growth of mobile network usage. Finnish people use the most mobile data in the world, with an average of 4.3 gigabytes per month, and the use of mobile data per month grew 61 % in the first half of 2015, compared to year 2014 (Tefficient, 2016). To meet the demand for high quality mobile services, Mobile Network Operators (MNOs) need to constantly improve their networks. Due to continous investments, 3rd generation (3G) technologies reach 99 % of the population and 4th generation (4G) networks reach 98 % of the population in Finland (Uitto, 2016).

However, no operator covers all of the possible area. There exist some areas with no cellular coverage, and areas with partial coverage, i.e., locations where one MNO has signal but another does not. There exists also a disparity in the technological offering of MNOs: one operator might offer only 3G in a certain location while another offers 4G. Thus, users experience differences between MNOs in availability and throughput. While urban areas have good coverage and capacity, rural areas and locations where no-one is living permanently, such as summer cottages and the archipelago, can have lower network quality.

This thesis explores the concept of flexible access, defined as the possibility of an end-user or device to communicate through the best available network when needed. With flexible access, mobile users can access multiple mobile networks. This improves resilience in locations with signals from multiple operators, since if one network suffers from an outage, communication can continue through another network. In addition, flexible access helps with the problem of network coverage disparities. Furthermore, by having access to multiple mobile networks, the user could flexibly and dynamically choose the better network based on certain network metrics, such as throughput.

One way to have flexible access to mobile networks has traditionally been to operate two mobile phones having subscriptions with different MNOs: one is used normally, while the other is only used e.g., at the summer cottage, where the first MNO has a poor service. However, it is not convenient for the end-user to manage multiple devices, and there exist better solutions to access multiple networks. The research interest of this study is in the benefits for and satisfaction of users with flexible access compared to single access. The main research question of this study is:

> How can utilizing flexible access benefit end users?

The main research question is split into two more specific sub-questions:

- How can mobile users benefit from the mechanisms of national roaming and end-user multihoming?
- How can the user benefits of flexible access be evaluated with agent-based modeling and simulation?

Based on these questions, this study has two objectives: First, to research two mechanims that can provide flexible access: national roaming and end-user multihoming, to investigate their current state-of-the-art and to compare the feasibility of the mechanisms to benefit mobile users. Second, to investigate agent-based modeling (ABM) and to create software for simulating the behavior of mobile users, and to study how flexible access affect user satisfaction.

A literature study and semi-structured expert interviews are conducted to explore the past development and current status of national roaming and end-user multihoming in mobile networks. The principal research method used in this thesis is agent-based modeling. The ABM method is explored and its feasibility for studying mobile usage scenarios is investigated. The aim is to experiment with ABM and to create a prototype platform for simulating the data consumption behavior of mobile users. A simulation model is built to add light to the research question of the user benefits of flexible access, by studying how user satisfaction is affected by employing more than one network.

The remainder of this study is structured as follows. Section 2 presents a discussion of national roaming and end-user multihoming based on literature. Section 3 presents the methodology employed in this thesis. Section 4 reports the findings of five expert interviews on the subjects of end-user multihoming, national roaming and on the benefits and need for flexible access in general. The creation of the agent-based model and its simulation scenarios are reported in section 5. Section 6 presents and analyzes the results of the simulations. The simulation is further discussed and the overall findings of the thesis including conclusions from the simulations, literature and interviews are deliberated in section 7. Finally, section 8 summarizes the study and gives propositions for further research.

2 Background

This section explores the necessary background related to the mechanisms of national roaming and end-user multihoming. The mechanisms are defined and their different application areas and use cases are presented. In addition, the feasibility of the mechanisms is discussed. Finally, a comparison of the mechanisms is given.

2.1 National Roaming

This section gives an overview of roaming in general, and then discusses the concept of national roaming, its different use cases, and the historical and current status of the mechanism. Furthermore, the feasibility of national roaming is examined from different viewpoints.

2.1.1 Roaming

Users access mobile services by subscribing to a mobile operator. The operator provides the user with a Subscriber Identity Module (SIM), which enables the user's device to connect to the operator's mobile network. This operator is called the home operator, and the operator's network is called the *home network* of the user.

Roaming is a service that allows user devices to work with networks other than their home network (3GPP, 2005). The network that a user roams onto is called the *visited network*, or in some literature (e.g., Buehler (2015)), the host network. Roaming is performed when the device is outside the coverage of the home network. Thus, roaming extends the coverage of services for the user. There are two main ways to perform roaming: international roaming occurs when a user accesses a network in a foreign country, whereas national roaming means roaming inside the country where the home network is located, using the network of another domestic operator. According to specifications (3GPP, 2015), national roaming can be allowed in the entire visited network or only in a specific region.

Roaming is possible because the home operator and visited operator have made wholesale roaming agreements, which are invisible to the user. The user is subscribed only to the home operator, and has no commercial relationship with the visited operator. The visited operator charges the home operator for supplying the roaming service, and the home operator then charges the user. For a more detailed overview on how international roaming works, see GSMA (2012*b*).

2.1.2 Use Cases

National roaming has been used or is in use in different parts of the world, such as in Australia, India, USA, and in several EU countries (ENISA, 2013). However, most countries do not employ national roaming, due to various reasons. The implementation of NR has issues, which are discussed in the next subsection.

According to a report by the European Union Agency for Network and Information Security (ENISA, 2013), national roaming has mainly been used for the following purposes:

1) Facilitating market entry
2) Mobile Virtual Network Operators (MVNOs)
3) Covering rural areas
4) Inter-regional cooperation
5) Emergencies

Each of these use cases is now discussed briefly.

Facilitating Market Entry

A public regulatory authority may use national roaming to aid new operators enter the market. The idea is, that for a certain period of time the customers of the entrant can have national coverage by roaming in another operator's network, while the new operator is building its own network infrastructure. This agreement is usually meant to be temporary, and after a few years, once the entrant's network has reached a certain coverage level, the roaming contract ends. With a mandate from the regulator to utilize an incumbent's network, the entrant can delay its infrastructure investments so that it has time make profits and gradually expand its network. The regulator should also set a limit on the tariffs the entrant pays for roaming. The reason for a regulator to facilitate market entry is to increase competition and decrease market concentration, which is thought to benefit consumers by lowering prices and improving service offerings of operators. (Sutherland, 2011; GSMA, 2012*a*)

Historically, national roaming was considered important with the advent of third generation (3G) technologies (Sutherland, 2011). When 3G licences were auctioned, the idea was to attract bidders outside the current incumbent operators by facilitating the entry of new 3G operators through national roaming. The incumbent operators already had the second generation (2G) infrastructure in place and could for example re-use their existing masts for 3G equipment installations, whereas a new entrant would start building the network from scratch and have much larger infrastructure costs. The regulator would ease the market entry of new operators by obliging incumbents to provide NR for the entrant's customers to their existing 2G networks. For example in the UK, the regulator let the operators conduct commercial negotiations amongst themselves but proposed a condition that if the negotiations do not include national roaming on existing 2G networks, the regulator will require them to provide it. As a result of the auctions in UK, a new 3G operator called '3' entered the market and made a 2G roaming agreement with the incumbent operator O2. (Sutherland, 2011)

Sutherland (2011) claims that while national roaming was considered necessary to facilitate market entry in Europe in the beginning of 21st century, it proved to be less important then the EU countries expected. He explains that the number of new operators was lower than expected, because building networks and acquiring customers had high costs, and after the information technology bubble bursted at the turn of the century, there was not enough funding for new infrastructure-building operators.

Mobile Virtual Network Operators

Mobile Virtual Network Operators (MVNOs) do not operate their own mobile network, but have made a wholesale agreement to utilize an MNO's network capacity. As opposed to the previously discussed market entrant case, a virtual operator does not aim to build its own wireless infrastructure but bases its business on exploiting the existing infrastructure of an incumbent MNO. Some sources, such as Sutherland (2011) and ENISA (2013) regard MVNOs as commencing in permanent national roaming, since they do not have their own access network. The operation of MVNOs differs from traditional roaming, though, because the MVNOs customers can only access one network, and do not have the resilience and coverage benefits as in normal roaming, where multiple roaming contracts have been agreed between operators.

There is also an approach called Multiple-Operator Mobile Virtual Network Operator (MO-MVNO), proposed, e.g., by DCMS (2014), where the virtual operator makes radio access agreements with multiple infrastructure-based operators. The service of an MO-MVNO is easier to be defined roaming, because the subscribers will be connecting to different networks while having a subscription to only one operator. The tecnology company Google has a new virtual operator called Project Fi, which can be considered an example of an MO-MVNO, since it has made agreements with three MNOs in the United States (Google, 2016).

Covering Rural Areas

Rural areas are more sparsely populated than urban areas, and therefore have less mobile subscribers. This leads to operators investing less in rural coverage. Often the case is that a certain place in the countryside has only partial coverage – some operators work but some do not. This is opposed to urban areas, where almost every location has signal from all operators, save for some problematic locations such as indoor locations. To address this issue, national roaming can be employed, so that if the home operator's signal is lost, the user can roam in a competitor's network. National roaming limited to rural area usage has been implemented at least in France (Analysys Mason, 2010) and in Australia (ENISA, 2013). In Finland, people travel outside cities for example to countryside summer cottages, wilderness in Lapland, and archipelago of the Baltic Sea, which are all rural areas that can have partial coverage.

Partial coverage results in inequality among the inhabitants within a country. The regulator in the UK states that the people who live in areas of partial coverage have less options for provider, mobile handsets and subscription packages than the people living under complete coverage (DCMS, 2014). Moreover, people visiting the areas are also affected by the lack of coverage.

Inter-Regional Cooperation

Most of India is covered by local and regional MNOs, which do not have a licence to operate in the whole country. Their subscribers use roaming when traveling in other regions. In addition, there are cases of intra-region NR when a regional operator does not have sufficient coverage. This is similar to the previously discussed case of treating partial coverage. Another large country, the United States has obliged the largest incumbent operators to offer national roaming services to smaller operators so that their subscribers will have national coverage when moving between states. Earlier the requirement was for voice roaming only, but now includes also data services. (ENISA, 2013)

In effect, the use of NR in these extensive countries is comparable with international roaming (e.g., in Europe). It is only semantics if the activity is called inter-regional, inter-state or international roaming, the point being that this type of roaming happens in distinct non-overlapping regions.

Emergency Needs

National roaming can be used in emergency situations such as network failures. In case one operator suffers from a network outage, their users can switch to a competitor's network until the the problem is fixed. Ad hoc roaming agreements have been made in emergencies on the Virgin Islands in the Caribbean Sea in 2013 and in the US for voice services after a hurricane in 2012. Three Dutch operators have made reciprocal emergency roaming agreements, where subscribers can manually activate national roaming in the two remaining networks if one network is disrupted. The temporary NR service supports voice and SMS traffic, but data traffic is not allowed, to prevent the visited networks from overloading.

There are some challenges with emergency NR, and overloading the visited network is one of the critical ones. Operators have measured their networks to service their own subscribers and the rather small number of users who use international roaming, but their capacity cannot support for example doubling the number of subscribers in case of an outage. If all the users from a failed network are freely allowed to use another network in an unchanged manner, it can lead to a domino effect where the next network collapses as well, and a third operator has to try to support users from two networks, which will definitely lead to another overload.

Sweden also uses NR for emergencies but does not even try to manage the problem with overloading. The Swedish regulator has agreed on a national roaming system where only a select four thousand SIM-cards are allowed to roam in case of an emergency situation. These SIM-cards are only for the use of authorities. (ENISA, 2013)

2.1.3 Feasibility

There are many concerns over the possible negative effects of national roaming. According to Borba Lefèvre (2008), NR can lead to similar retail offerings between operators, because operators want their users to be served in the visited network with the same quality of service (QoS) as in the home network. Since roaming agreements are reciprocal, the home and visited operator will agree on the QoS requirements. As a result, there will be less differentiation between the QoS of the operators.

NR can also hinder price competition, as the retail prices are a result of wholesale roaming prices that the operators have agreed on (Borba Lefèvre, 2008). If the QoS levels are agreed to be similar due to reciprocity, the wholesale roaming pricing is likely to be mutually similar, resulting in decreased price competition. However, these effects occur only in the areas where NR is employed. Thus, if NR takes place only in a small fraction of locations, it will doubtedly have a large effect.

Borba Lefèvre (2008) states that NR can be implemented feasibly, for instance by covering rural areas with roaming while each MNO builds its own infrastructure in urban areas. Covering certain remote areas can be very costly for operators and some customers might not be covered at all. According to Borba Lefèvre (2008), with NR, these areas can probably be covered more affordably. Related to this, there is a joint venture by two main operators in Finland to cover eastern and northern areas of the country: they are building a common network where their customers will be roaming in, resulting in lower construction costs (Finnish Shared Network, 2016).

A report by consultancy firm Analysys Mason (2010) to the regulator in UK discusses the issues and impacts of national roaming. The report presents results of a questionnaire which inquired on the technical as well as commercial feasibility of NR, and is recommended further reading for anyone interested in the subject.

2.2 End-User Multihoming

This section discusses the concept of multihoming, defines the term end-user multihoming used in this study, and gives examples of how it can be employed by end-users. In addition, the feasibility of end-user multihoming is discussed. Since the terminology in the field of communications is often variably used by different authors, let us begin by explaining some key terms.

2.2.1 Multihoming

In general, multihoming means that a network entity, be it a single device or a network of devices, can connect to the Internet through multiple networks and send and receive data through them. There are many levels of abstraction and points of view to characterize multihoming: On a technical level, an internet host is multihomed if it has multiple Internet Protocol (IP) addresses (Braden, 1989). This is analogous to an individual having multiple homes if he has multiple home postal addresses. According to Suomi (2014, p. 3), multihoming on a business level means the ability to communicate through multiple Internet Service Provider (ISP) networks, thus having multiple business agreements. Multihoming can be thought of as means to reach online services through alternative access networks – for example with modern smart phones the Internet can be accessed through different cellular networks or wireless local area networks (WLANs).

Closely related with the concept of multihoming is multipathing, and it is easy to confuse the two. Suomi (2014) states that multipathing in general means that there are multiple differing end-to-end paths used in communications, and there are various solutions that can be described as multipath. A key characteristic is that in multipathing, the multiple network connections, i.e., paths, are used simultaneously (Suomi, 2014; Sonntag, 2016). Sonntag (2016, p. 15) distinguishes multihoming from multipathing by defining that in multihoming, a network entity has the possibility to use multiple networks, but only one network at a time, while in multipathing the networks are used in parallel.

The term *end-user multihoming* refers to those multihomed devices that have a human end-user, such as personal computers and smart phones, and excludes networks of devices and devices that do not have a user interface. In the scope of this thesis, end-user multihoming refers only to mobile users who are connected to mobile phone networks through cellular technologies. Fixed-line communications and other wireless communications, such as WLANs and satellite communications are left outside the discussion. End-user multihoming in this study is defined as the ability of an end-user device to access multiple cellular networks, operated by different Mobile Network Operators (MNOs). Basaure et al. (2016) view end-user multihoming to be a user-driven market mechanism. The capability of the end-user to be multihomed depends on the user device, and users can choose to use multihoming-capable devices. The network operators cannot directly control the adoption of multihoming devices by users. Thus, end-user multihoming can be regarded as a user-driven approach to flexible access.

2.2.2 Use Cases

End-user multihoming is currently used with multi-SIM devices, which support installing two or more Subscriber Identity Modules (SIMs) inside the device. These devices can be divided into passive and active multi-SIM devices. Passive multi-SIM devices can only communicate through one network at a time, since they only have one radio, and have to alternate between networks. Active multi-SIM devices, on the other hand, have multiple radios and can communicate through multiple networks in parallel. Thus, passive multi-SIM devices enable multihoming while active multi-SIM devices enable both multihoming and multipathing. (Sonntag, 2016)

Multihoming can increase the network availability and throughput. Availability is increased just as with national roaming, because if one network does not have coverage at a certain location, or if one network suffers from an outage, another one can be used. Research by Sonntag (2016, p. 74) states that anywhere in Finland the probability of attaining a 100 kbit/s speed is almost 100 % with end-user multihoming. Thus, multihoming can be used for coverage and resilience purposes. Transmission speeds can increase if the networks have differences in throughput – with an active multi-SIM device, a dynamic interface selection mechanism can be employed to choose the better network.

When a device has multiple networks at its disposal, the question is which network to use, and how to choose the network. A user may want to for example maximize the throughput at a certain location or to choose the network with lowest price. According to research by Sonntag (2016), signal strength is not an applicable measure of throughput – it correlates with throughput only up to a certain signal strength level, after which it is not useful for determining the fastest network. The technology used by the base station is more important for determining the maximum possible throughput. The network can also be chosen by conducting test data transmissions and by comparing the achieved throughputs. Testing is not optimal in the case of a passive multi-SIM device with a single radio, since running a test will occupy the network interface and use time from the actual data usage. Thus, the device has to alternate between the actual data and testing data. However, an active multi-SIM device can have a data session on one interface while conducting tests on the other interface. As a result, live testing is more usable through multipathing than through multihoming. Sonntag also states that instead of doing live tests on the go, multihoming users could exploit a database filled with previous historical metrics for networks in different locations, which could be employed for the selection of network. (Sonntag, 2016)

The end-user service can be made more dynamic with mobility and multipath protocols (Basaure et al., 2016; Sonntag, 2016). Mobile Internet Protocol (MIP) and Host Identity Protocol (HIP) offer better resilience by enabling the change of network without breaking the connection, and throughput can be increased with MIP by choosing the best available network and switching traffic between networks (Sonntag, 2016, p. 42). Furthermore, there is a protocol designed for multipath communications, Multipath TCP (MPTCP), which is a set of multipathing-enabling extensions to Transmission Control Protocol (TCP) (Ford et al., 2013). MPTCP can be used for both multihoming and multipathing (Sonntag, 2016). Suomi et al. (2013) envision that multipath protocols could switch between the networks in a matter of seconds – with multiple radios, MPTCP could monitor the quality of the networks and optimally choose the best network. However, this would require multipathing and an active multi-SIM device, but it is natural for device offerings to develop, and evolution of the market can happen at some point in a way that the number of active multi-SIM devices increases. Suomi et al. (2013) also see the prospect of modifying multipath protocols to take into account the price information of operators in network selection. In this use case, the the end-user could optimize the price and quality of the mobile service with real-time information about the throughputs and prices of different networks. These are interesting future visions.

Use of multihoming can also develop due to advancements in SIM technology. The SIM card is evolving into an embedded SIM (eSIM) in macine-to-machine (M2M) communications (Vesselkov et al., 2015). The eSIM introduces remote subscription management, which means that the mobile operator profile of the SIM can be reprogrammed with over-the-air provisioning. This is a major shift, because with a traditional SIM, the physical SIM card itself has to be changed manually in order to change the mobile operator subscription if the device. The introduction of eSIM to M2M devices is motivated by the fact that manually changing the SIM cards of M2M devices is costly – many M2M devices are in remote locations and it takes time and money to send maintenance personnel to change the SIMs when the M2M service provider wants to change the MNO (Vesselkov et al., 2015). Changing the operator with the traditional SIM card also costs time and money for consumers. The eSIM and possibility to change the MNO remotely would dramatically lower the consumer switching costs compared with the manual changing of SIM cards. If the change of subscription could be developed to take only seconds, eSIM could at least partly replace the need for multi-SIM devices.

2.2.3 Feasibility

The evolution and use cases of end-user multihoming (and multipathing) described above require multi-SIM devices with multiple radios and support for multihoming and multipath protocols. The MIP and MPTCP protocols require server-side modifications, while HIP has problems with Internet interoperability (Sonntag, 2016; Suomi, 2014). Even if end-user devices would have the needed protocols installed, it will take time for the protocols to be diffused to enough servers. The adoption of dynamic interface selection requires devices to have at least dual radios to be feasible.

If user devices have more than one radio, they will be consuming more energy when using multipath communications. Thus, the battery of the device will be depleted faster, requiring more efficient batteries to be developed or larger batteries to be installed in devices. With end-user multihoming, where only one network is used at a time, however, the energy consumption will not increase so dramatically. The dual radios could only be used for testing for a better connection when needed, and otherwise a single network would be used at a time, to save the battery. Therefore, end-user multihoming could be more feasible to implement than simultaneous multipathing.

New devices with more radios and better or bigger batteries would probably cost more. To lower the prices, sufficient demand should exists for the devices. This brings us to the question of how wide is the need for flexible access and will end-user multihoming be ever adopted by the masses. The expert interviews in section 4 discuss these aspects more.

2.3 Comparison of End-User Multihoming and National Roaming

National roaming and end-user multihoming are both possible mechanisms to offer flexible access to end users. Table 1 summarizes differences between the two mechanisms. Basaure et al. (2016) have compared national roaming and end-user multihoming (along with dynamic spectrum access), and made the observation that multihoming is a user-driven approach while national roaming is enabled by operators, who have to have agreements in place for users to employ roaming.

From the business perspective the two mechanisms have different consequences on the market. The basic difference is that in NR the user has a business relationship only with the home operator – that is, the user pays only to the home operator, which, in turn, pays to the visited operator – whereas in host multihoming the user pays directly to the operators which he/she uses. MNOs need to cooperate to sign the roaming agreement, and the investments and competition could decrease. In contrast, end-user multihoming could increase operator competition.

From a technical point of view, national roaming and end-user multihoming could be considered as a similar flexible access service to the user: they both enable connecting to more than one network. When we look deeper though, there are differences. In NR, the network selection is based on signal strength, and roaming is engaged only when the main operator's signal is lost. Multihoming, on the other

Table 1: Comparison of national roaming and end-user multihoming.

Flexible access method	National roaming	End-user multihoming
Market mode (Basaure et al., 2016)	Operator-driven	User-driven
User business relationship	With one operator	With multiple operators
Network selection based on	Signal strength	Signal strength, Technology, Speed tests, Pricing
Wholesale agreements between operators	Yes	No
User QoS benefits	Improved availability	Improved availability and throughput

hand, supports network selection also based on the technology and measured speeds, and even pricing in futuristic scenarios.

The benefit for end-users would be better availability and resilience with both mechanisms. End-user multihoming could, in addition, improve the throughput by selecting the faster network, but it requires some implementation of dynamic network selection to be used. Of course many options are technically possible, and national roaming could be made more dynamic by letting the user choose the network to be used. However, there are not many reasons why operators would support this. In summary, both mechanisms can offer benefits to end-users and increase their satisfaction with the mobile service. End-user multihoming, and especially multipathing, offer more options to increase the quality of service than national roaming. However, the future developments in the adoption of the mechanisms are unclear.

3 Research Methods

This thesis applies the method of agent-based modeling (ABM) and simulation. In addition, interviews are employed to expand on the background literature. However, interviews are only a supporting method, and this section focuses on explaining the ABM method, whereas the interviews will be discussed in section 4.

3.1 Modeling and Simulation

Before explaining ABM, it is good to discuss what is modeling and simulation in general. Law and Kelton (2000) state that there are two options to study a system: one can either experiment with the actual system or experiment with a model of the system. Most often it is infeasible to experiment with an actual system, and thus humans create models. In short, a model is a simplified representation of a system. Law and Kelton (2000) divide models into physical models and mathematical models while Singh (2009) divides them into physical, mathematical and computer models. The models created in this thesis are mathematical and computer models. According to Law and Kelton (2000), a model comprises of a set of assumptions about the system under study. With some simpler models, a researcher can analytically and exactly answer his questions by using mathematical methods, but with many complex systems, the assumptions of the model are numerous and complicated, and the system has to be studied through simulation (Law and Kelton, 2000).

Simulation has many definitions, and one is that simulation imitates the behavior and operation of a system (Singh, 2009; Law and Kelton, 2000). Singh (2009) states that simulation is simply the exercise of conducting experimental trials with computers. In simulation, the operation of a model is studied by introducting different inputs to the model and seeing how they affect the outcomes. Law and Kelton (2000) define a simulation model to be a mathematical model that is studied with simulation. They divide simulation models into static and dynamic. Static simulation models can portray systems where the passing of time is not relevant, while a dynamic simulation model demonstrate the behavior of a system over time. The simulation model created in this study is dynamic, and simulates the behavior of mobile users during a certain time period.

Grim et al. (2013) partition the structure of a simulation into three parts: input conditions, mechanism and output conditions. Thus, there is a beginning and end to the simulation, and one transtition from the inputs to the outputs is called a simulation run. Input conditions are the configuration of the simulation model at the beginning, before time is let pass. Output conditions are the configuration of the simulation in the end, after the simulation run has stopped. Mechanism is the way how the simulation creates the output from the input during the simulation run.

According to Grim et al. (2013), there are four scientific goals of simulation: prediction, explanation, retrodiction and emergence explanation. In prediction, present and previous data is used as input to acquire a prediction of the future as output, such as in weather forecasting. In explanation, the input and output data are known, and the purpose is to find the mechanism that led from the inputs to the outputs. Retrodiction aims to investigate the historical state of the world, for instance, if an asteroid destroyed dinosaurs or not. The fourth goal of simulation is emergence explanation. It studies how complex phenomena can emerge from a set of simple rules.

Grim et al. (2013) note that it is important to understand how the different goals of simulation differ in terms of which of the three parts of simulation structure – inputs, mechanism and outputs – is a source of new information. In prediction, the output is a source of new information, while the inputs and the mechanism are regarded as already known. In explanation, the source of new information is the mechanism, while in retrodiction, the input conditions of the simulation are a source of new information. With emergence explanations, both the inputs and the mechanism represent new information.

3.2 Agent-Based Modeling

Agent-based modeling (ABM) is a modeling technique where the modeled system consists of interacting agents. An ABM system displays properties, which emerge from the interaction of the agents, and which can not easily be deduced from the properties of the individual agents (Axelrod and Tesfatsion, 2006). This emergent behavior means that the whole is more than the sum of its parts. ABM can be applied in a variety of social, physical and biological systems and has a number of applications, e.g., in markets, supply chains, organizations, warfare, the spreading of diseases and the diffusion of innovations. The agents can be modeled as humans, i.e., consumers, voters, farmers or soldiers, or they can represent larger entities such as communities, companies or governments. (Macal and North, 2009; Bonabeau, 2002)

The ABM method is a bottom-up approach, where the micro-level behavior of agents result in observable macro-level phenomena. Bonabeau (2002) calls ABM "microscopic modeling". Thus, the properties and behavior of the agents need to be defined rigorously, because their decision-making and interaction will produce the higher level results.

Axelrod and Tesfatsion (2006) state that whereas the traditional two ways of advancing science are deduction and induction, simulation, and especially ABM, is a "third way of doing science". In simulation, theoretical assumptions need to be devised as is done in deduction. These assumptions are the input of the simulation, and after running the simulation, the output data is analyzed as in induction. Unlike in traditional induction, the data is not real-world data, but it is a product of the assumptions made by the modeler. Unlike in deduction, the assumptions (theory) are not tried to be proven, they are only the input to the simulation. However, because the outcomes of the simulation are solely based on the inputs, these assumptions need to be rigorously defined. Eason et al. (2007) disagree that simulation is separate from the traditional scientific practice and state that science uses whichever techniques that are available and useful. In their view, dividing science into induction or dedcuction is oversimplifying what science is.

ABM models can range from simple models trying to capture essential features of a system based on idealized assumptions to large systems meant to support decision-making. The smaller models can explore many alternative assumptions and be more experimental, while the decision-support systems include real data and are validated to be credible. (Macal and North, 2009)

When making a simple model, it is a considerable challenge to focus on the most important assumptions and discard the unnecessary ones, as it is easier to add features to a model than to remove them. Varian (1997) says that creating a theoretical model is like working on a sculpture: it is mainly a process of iteratively removing pieces to make the model clearer. Larger ABM models can try to be more realistic and for example in the context of mobile networks a model could have real-world geographical data and base station locations and technical parameters as input. The model in this thesis is somewhere in the middle, with certain simple assumptions and some more detailed behaviors.

This thesis follows the informal definition of an agent as described by Macal and North (2009). According to the authors, the definition of what constitutes an agent has been long discussed and there is no clear consensus on what suffices as an agent-based model. There are many definitions of an agent, but usually an agent is an independent actor that is self-directed and has autonomous behavior. An agent has to be a discrete, self-contained and identifiable individual. The agent interacts with other agents: in addition to its independent behavior, it has to have rules in place which control how the agent reacts to the behavior of other agents. There are also properties and attributes that an agent may have, but not necessarily has. An agent can exist in an environment and interact with the environment as well as with other agents. An agent can have pre-defined goals that it tries to accomplish. Furthermore, the agent may have memory, and be capable of learning and adapting its behavior based on knowledge of the past. Adding all these additional properties depends on how refined the model needs to be. (Macal and North, 2009)

Constructing an Agent-Based Model

According to Macal and North (2009), building an agent-based model starts with identification of the agent types, definition of their attributes and specification of their behavioral and interaction rules. The agents can be identified by considering who or what are the relevant decision-makers in the system. The attributes are defined by deciding what are the relevant properties of an agent. For example, a mobile user usually has knowledge of which operator's service it is using. Thus, a user agent could have a subscription attribute to hold the name of the operator. The behavioral rules of agents should be based on relevant theory in the field. Finally, the methods for agent interaction should be developed: they define when and how agents interact with each other and which of the agents interact.

The structure and topology of the agent-based model needs to be decided. Among different possible topologies are an aspatial soup model, where agents have no representation of their location, a von Neumann neighborhood topology, an Euclidean space topology, where agents move in a two or three-dimensional space, a geographic topology representing a realistic landscape, and a network topology. The topology should be carefully chosen based on how realistic the simulation model needs to be in order to study its relevant aspects. For example, building a realistic geographic topology consumes more time and resources than modeling agents in a simple von Neumann grid neighborhood. (Macal and North, 2009)

To create an ABM model in practice, suitable computer software needs to be found and employed. Modeling can be carried out with general-purpose programming languages or with ABM-specific software and toolkits. Depending on the size of the modeling project, simulations can be run on a desktop computer, or if the simulation demands more computing power it can be run on computing clusters. According to Macal and North (2009), it is natural to begin with a small model on a desktop at first and to then expand it gradually.

Agent-based modeling and simulation should be considered as a research method for instance when the research problem can be naturally thought of as consisting of agents, when the decisions and behavior of the agents can be accurately defined, when it is important that agents have dynamic, i.e., changing relationships with other agents, when spatiality and location is important to agent interaction and when adapting behavior of agents is important (Macal and North, 2009). All these criteria suit the study of mobile network usage scenarios from the user perspective. Therefore, ABM was chosen as the method for this thesis.

4 Expert Interviews

Five separate expert interviews were conducted to obtain insights on flexible access, and specifically end-user multihoming and national roaming. The experts were interviewed face-to-face in April 2016 and each session lasted from one to one-and-half hours. Two interviewees worked for Finnish network operators and two interviewees for the public communications authorities of the Finnish government. The fifth interviewee wished to remain anonymous. Table 2 lists the organizations and fields of work of the persons interviewed. It also defines a short code for each interviewee, which will be used to refer to the interviewees in the text.

The interviews were semi-structured, meaning that a list of topics and questions to be followed were prepared in advance, but certain topics were pursued to more extent and some questions were skipped, if it was seen reasonable by the interviewer. Thus, each interview was unique and stressed different topics depending on interview dynamics. The higher level structure was the same for each interview. First, using multiple networks was discussed in general. Second, the interviewee was briefed on the research topic and some basic terms where defined. Third, multihoming was discussed, along with multi-SIM and eSIM and the market effects of a user-driven solution. The fourth topic was national roaming (NR), its technical feasibility, and benefits and challenges. Finally, the pricing of the mechanims of multihoming and NR was discussed, since one of the original goals of the thesis was to explore the future pricing schemes and their effects. The pricing perspective was later excluded from this study. One of the original ideas was to include pricing of mobile subscriptions in the agent-based model. However, the topic was narrowed down due to time and effort constraints. A list of the interview topics can be found in appendix A.

Table 2: List of interviewees.

Code	Organization	Field	Interview Date
OP1	Network operator	Radio network planning	13.04.2016
OP2	Network operator	Radio network planning	15.04.2016
R1	Government regulator	Communications networks	11.04.2016
R2	Government regulator	Communications networks	07.04.2016
Anon	Anonymous	Anonymous	19.04.2016

4.1 Benefits and Challenges of Flexible Access

The main two benefits of using multiple mobile networks were seen to be increased coverage and capacity. All the interviewees stated that coverage would improve with multiple networks, since there always exist some coverage disparities between operators, i.e., locations where one operator has signal and another does not. None could estimate how much the coverage would improve and exactly how beneficial it would be to users. OP2 pointed out that even if an operator has certain coverage at a certain point in time, the coverage is not stable due to changes in the physical environment. Society develops and new infrastructure is constantly being built; for example, modern houses can be constructed to a location that earlier had an open field, which might result in problems in signal reception. He also remarked that using multiple networks will not help in case no operator has coverage at a certain location.

The second possible benefit of flexible access is increased capacity. Technology implementations and data speeds between operators differ, and depending on time and location, a user can get a higher speed by switching to another network. However, R1 noted that there is no guarantee of higher speeds: the speed could also be lower. The other operator may have newer technology and offer more capacity, but the opposite could also be true. Furthermore, most interviewees commented that the benefits of the possibly increased data speeds are hard to estimate. The question still remains that if using multiple networks would result in increased coverage and speed, then how much, and would it be worth the effort of developing a flexible access service further. OP1 noted the prospect of aggregating the capacities of multiple networks through simultaneous multipathing, which was earlier discussed in section 2.2.

OP2 claimed that planning the network capacity would be more difficult if users were able to access multiple mobile networks. Already because of the nature of mobility, it is a challenge for the operator to dimension the network so that the right locations have the right amount of capacity to serve the demand. Users switching between networks would make the estimation of demand even more difficult for the operator. He continued that this would be the case with a large number of multi-access users – a smaller number, such as the current users of international roaming, does not so greatly affect the sizing of capacity.

OP2, R2 and Anon described the mobile networks in Finland to be very good compared with the rest of the world. Thus, in their view, lack of coverage is not such a significant problem in Finland. OP1 saw the coverage problems to be more relevant in the countryside, e.g., at summer cottages, and he knows some people who need to have multiple subscriptions because of the disparity in coverages. R1 stated that some Finnish consumers do have a need to use multiple mobile networks, and he himself has subscriptions of multiple operators because of differences in data speeds between operators. According to R1, the indoor coverages have significant disparities. Three interviewees saw indoor coverage as a challenge that every operator has problems with, especially with modern energy-saving buildings. According to OP2, operators are working hard to establish good indoor coverage.

4.2 Views on End-User Multihoming

The term multihoming was not very familiar with most interviewees and the interviewer struggled with the definition and was not able to make sure that the correct one of the two multihoming cases was discussed. One case of multihoming is the case comparable to current multi-SIM devices, which have two (or more) co-existing mobile subscriptions. In this case, using multiple networks is meant to mean the switching between the two subscriptions, through some sort of dynamic interface selection. The other case regards the embedded SIM (eSIM) and the possibility to change the subscription completely from one operator to another, while having only one subscription on the device at a time. In this case, when the device wants to use another network, the customer contract with the current operator is ended and a contract is made with another operator, through remote provisioning.

The embedded SIM card was discussed in some interviews. R2 saw that eSIM, which has standardization almost ready, will first enter the M2M market only, but could probably come to the consumer market at some point. R1 and R2 stated that operators will oppose eSIM for consumers because it eases the change of operator. Operators prefer to keep their customers and oppose a solution which reduces switching costs of customers. As a historical example, R1 mentioned the introduction of number portability, which was resisted by operators. The easier the switching is the less loyal the customer becomes, unless the operator holds some competitive advantage. Thus, eSIM would probably increase competition (R1). According to Anon, an extreme solution of remote provisioning that allows customers fast changing of operator as soon as they see a better offer – possibly done automatically – would lead to intensive price competition. Lowering prices would result in operators trying to minimize costs, e.g., by decreasing investment and maintenance costs. R1 wondered how fast the change of subscriptions could be, since it also includes legal aspects, since ending the old contract and establishing a new one should be legally valid. OP2 mentioned that there is at least a delay in updating customer registers, and speeding up the process needs coordination among operators.

Discussion of having multiple subscriptions on one device and being able to dynamically switch between them brought forward many questions. Among them were: How would the network selection be triggered? How to know if the other network is better? How to guarantee QoS? Which operator to blame in case of bad QoS? Coverage problems could be mitigated by measuring signal strengths, but the quality would not be quaranteed. Thus, to find out if the other network offers faster speeds, the throughput would need to be measured with a test. One interviewee (Anon) noted that background speed tests, if done with a device with a single radio interface, would consume resources and lower the QoS. Thus, one should carefully consider when speed tests are feasible, and only make tests when the network quality is low. Two separate connections could be maintained by having two radios on the device, but that would increase battery usage and possibly the weight of the device (R2). If some users tried to maximize their service quality by rapidly switching between networks, it would be a capacity sizing issue and guaranteeing a certain QoS level would be challenging (OP2). Another respondent (OP1) raised the question that if dynamic interface selection occurred without the user's awareness, which operator would the user complain to in case of bad network quality? If the user did not know which network he was using, it would require communication between the operators to determine the cause of the error. However, in case of a mere coverage problem where a user lacks signal, e.g., visiting a summer cottage, the network would be switched only once and kept during the visit. This would be a simpler use case than trying to acquire a faster connection by actively measuring data throughputs.

The interviewees identified few business and regulation impacts of multihoming. Due to the limited perceived need and benefits of multihoming, it was seen as a niche market. R1 and R2 stated that there is no need for new regulation regarding multihoming, but R1 continued that if there would be increased need to let consumers more freely switch operators, it would probably require obligations by the operator. Costs of new technology will ultimately be paid by the end-users (R2), and it is a question of how much users are willing to pay for this type of service (OP2). Anon stated that in the end, the customer ends up paying for the costs of regulation. If users would have multiple subscriptions, R2 suggested operators would be satisfied due to more subscriptions meaning more revenue. In the case of eSIM enabling multiple operator profiles and if metered pricing was used, the revenue would be split between the operators, depending on usage. With fixed pricing, the operators would benefit since usage would still be split – and would be less per operator – but the revenue would remain the same.

4.3 Views on National Roaming

According to the interviews, it should be possible to implement NR in a similar way as international roaming. None of the interviewees were experts on roaming matters and could only offer their best guesses, but they all thought that the two concepts should be implementable with the same technology, and could not think of technical differences between NR and international roaming. It was speculated that roaming could be a basic feature of network equipment, but the vendor might also have it as an optional feature, activating of which might result in extra costs for the operator (OP1, Anon). The interviewees were not sure if national roaming could be provided only in certain areas. OP2 was uncertain if it is possible at all, while R2 and Anon guessed that in theory it could be limited to certain areas, possibly to certain base stations.

The benefit of NR was seen to be the increased coverage for users. Especially the public authority users, such as the policemen, firemen and ambulances would benefit, since they have more need for coverage (R2). The roaming mechanism would switch to a another network only if the signal of the home network was lost. Therefore, even if a competitor would have more capacity to offer, but the home operator has coverage, roaming would not be activated, since national roaming does not have a mechanism for selecting the fastest network. R1 saw that NR could be a possible solution to mitigate problems with indoor coverage. A theoretical benefit of NR to operators would be splitting the country geographically: for example three operators could only build their network in one third of the country and use roaming in the other two thirds (R2). However, this will not be permitted by regulators, and the regulator's intention in Finland has been to have three operators that each have nation-wide coverage, in order to have competition in the market (R2).

It was agreed that national roaming has challenges and possibly negative effects on the market. Three interviewees echoed the view found in literature that NR would decrease and slow down infrastructure investments and maintenance of networks, when operators could rely on the other networks more (OP1, OP2, R2). With new technologies, such as 5G arriving to the market, operators might delay investments and first watch what the competitors are doing (R2). Hence, it would slow down the competition between operators, and delay the technological advancements. In addition, operators could focus network investments in more profitable areas and use roaming in less profitable areas. This sort of price skimming was speculated on by OP1, OP2 and R2. R1 and OP1 mentioned an impact on competition, which might benefit customers: operators would no longer be able to compete with coverage, which would shift the focus of competition more toward their service offerings.

R1 thought that some of the negative effects of NR could be mitigated through correct pricing: when the roaming prices between operators are high enough, they need to consider more carefully if investing on their own network is more feasible than roaming. Therefore, through price regulation, roaming can be enabled or disabled, but the pricing needs to be a compromise where neither operator benefits too much from the roaming agreement (R1).

With two interviewees, limiting the use of NR to special cases was discussed further. OP1 doubted that NR could be limited to only emergencies, that the device would not know when losing the signal is due to outage and when it is due to a normal coverage problem. Anon stated that the user could force the device to stay on the visited network, and continue roaming despite the home network becoming available again. Since network selection is up to the device and the visited network can not know if the home network is available or not, users could misuse national roaming meant to be used temporarily by locking on to the visited network.

The prospects of Multi-Operator MVNOs was discussed with two interviewees. OP1 doubted that operators would want to be part of an MO-MVNO scheme with their competitors, and stated that there would be now guarantee that users would evenly roam in all the operators networks. If the users roam only in competitors networks, what is the benefit of joining the MO-MVNO scheme? R2 was convinced that the incumbent operators will not support the introduction of MO-MVNOs in Finland.

R1 remembered that Finland had had legislation in place for NR with 3G. Indeed, the *Communications Market Act 393* (2003, § 34) contained obligations to operators of significant market power to discuss, upon request, national roaming in their GSM network with an operator that has a 3G licence. This is one case of regulators trying to facilitate the market entry of new operators, as discussed in section 2.1.2. No evidence was found if NR was used according to this law in Finland. R2 and Anon doubted that NR has ever been used in Finland. The current Finnish legislation in the *Information Society Code 917* (2014) has no mention of national roaming.

National roaming faced opposition from most interviewees. Two respondents stated that NR should not be permitted in Finland (R2, OP1). A third one said that one should be careful when considering NR (Anon). OP2 saw that NR would benefit only a small group of users which would result in the consumer prices being high. Thus, not many consumers would be willing to pay for roaming. Some interviewees agreed that many solutions which are technically possible and seem reasonable at first might not be implemented due to business reasons and trade politics (OP1, OP2, Anon).

The expert interviews gave multiple insights to add to the previously examined literature. The future of end-user multihoming still seems vague and it is hard to predict what will happen in the consumer market with the introduction of eSIM. Adoption of national roaming is seen as undesirable development, and it has been known to have problems in the past. However, regulators and operators could agree on a form of national roaming which could give the needed benefits to end users without disturbing the competition, but it would require considerable efforts, and would probably be organized only if other endeavours seemed unfruitful. End-user multihoming is more likely to be employed by users in the near future.

5 Simulation Model

This section describes the created agent-based model and simulation. The idea is to simulate the data usage of commuting mobile users during their workday, while they move between home and workplace, and to measure how satisfied the users are with their Quality of Service (QoS). The goal of the simulation is to compare the satisfaction of users between different simulation scenarios, where certain parameters of the model are varied. The four possible goals of simulation were discussed in section 3.1, and here the goal is prediction, i.e., the model tries to predict the satisfaction of mobile users, and the output of the simulation is the source of new information. The model is a prototype where a number of assumptions have been defined: they are the input conditions and the mechanisms of the simulation model. Section 5.1 explains the assumptions.

5.1 Defining the Model

The basic assumptions of the model are that it is user centric, has no mechanism dependencies and employs single or flexible access for all users. User centric means that most of the assumptions regard user behavior, and the behavior of operators and their interaction with each other is not modeled. Operators are only represented by their base stations which serve mobile users. The model does not implement either the mechanism of end-user multihoming or the mechanism of national roaming, but has a more general representation of flexible access. In different modeling scenarios, all of the users always use either single access or flexible access. Thus, experiments where the number of flexible access users is gradually increased are not explored.

Agent-based modeling starts with the identification of the agents. This model has two main types of agents: mobile users and base stations. Both types have specific actions they take at each time step of the simulation. In addition, there is an observer agent, which coordinates the behavior of the user and base station agents. The attributes and behavior of the agents are defined in the following subsections. In addition, the model of how time progresses in the simulation is described, and the model parameters to be studied are presented.

5.1.1 Model Environment

To get a grasp of what the model looks like, let us begin by describing the environment where the users and base stations exist in. The simulation model is an Euclidean space model comprising a two-dimensional 'map' of rectangular tiles. One tile is modeled to have an area of 250 m $\times$ 250 m. The total area is 25 km $\times$ 25 km = 625 km^2. In the center of the environment lies a circular central area, which hosts the work locations of users. The diameter of the central area is 6 km. Every mobile user agent has a home location and a work location, which are set randomly in the setup phase of the simulation. Users' homes are uniformly distributed anywhere on the map and users' work locations are uniformly distributed inside the central area, which represents a city center. Two users can have the same home or work location.

Figure 1 presents an example of the model environment with the home locations visible as red squares and work locations as green squares.

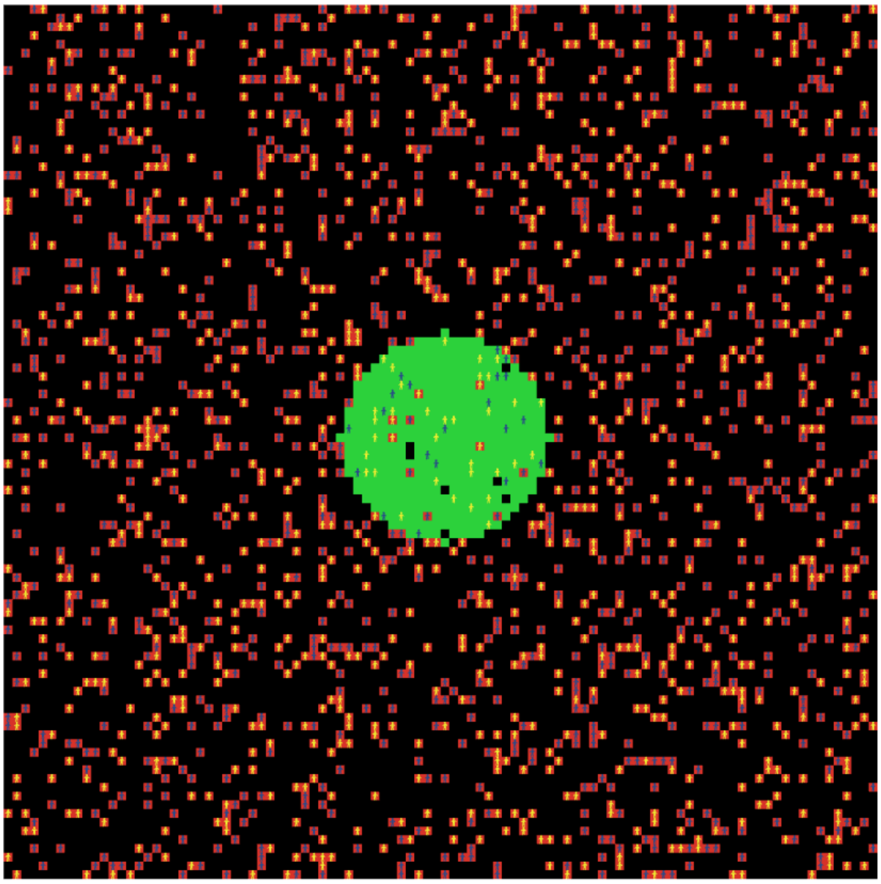

Figure 1: Model environment with an example of 2000 users. Red tiles are homes and green tiles are workplaces. Small yellow and blue figures are the users. Note that in the center, some homes and workplaces share a tile, and the color of the tile is either red or green.

The map is populated by two types of base stations. The central area has base stations with a range of 0.5 km and the rest of the map is populated by base stations with a range of 1.75 km. Inside the central area, the base stations are deployed every 0.5 kilometers, randomly inside a radius of 0.25 km. This means that every 0.5 kilometers there is a spot for a base station, but the BS is not actually in that spot but is located randomly in a location inside a circular area that has the spot as the center and has a radius of 0.25 km. Outside the central area, the base stations are located every 2.5 kilometers randomly inside a radius of 1 km. This approach creates a BS distribution that has a rather regular structure, but has some randomness compared to the base stations being in straight rows and columns. The randomness creates coverage disparities between the two operators and some areas with no coverage.

Figure 2 shows a screen capture of the environment, where yellow triangles represent base stations of one MNO and blue circles represent base stations of a second MNO. Yellow areas have only coverage of the first MNO, whereas blue areas have only coverage of the second MNO, and the green area has coverage of both MNOs. Areas with black color have no coverage. The base stations have two different shapes – triangle and circle – only for the practical reason that base stations sharing the same location can be seen, either by a circle showing under a triangle or vice versa. The simulation randomly decides which shape is shown on the top layer, but it has no significance whether a triangle is visible on top of a circle, or vice versa. Since the base stations are randomly located locally, the coverage areas of MNOs change with different random seeds. The environment comprises 418 base stations. The model has a total of 10 000 users of which 5000 are subscribers of the first MNO and 5000 are subscribers of the second MNO.

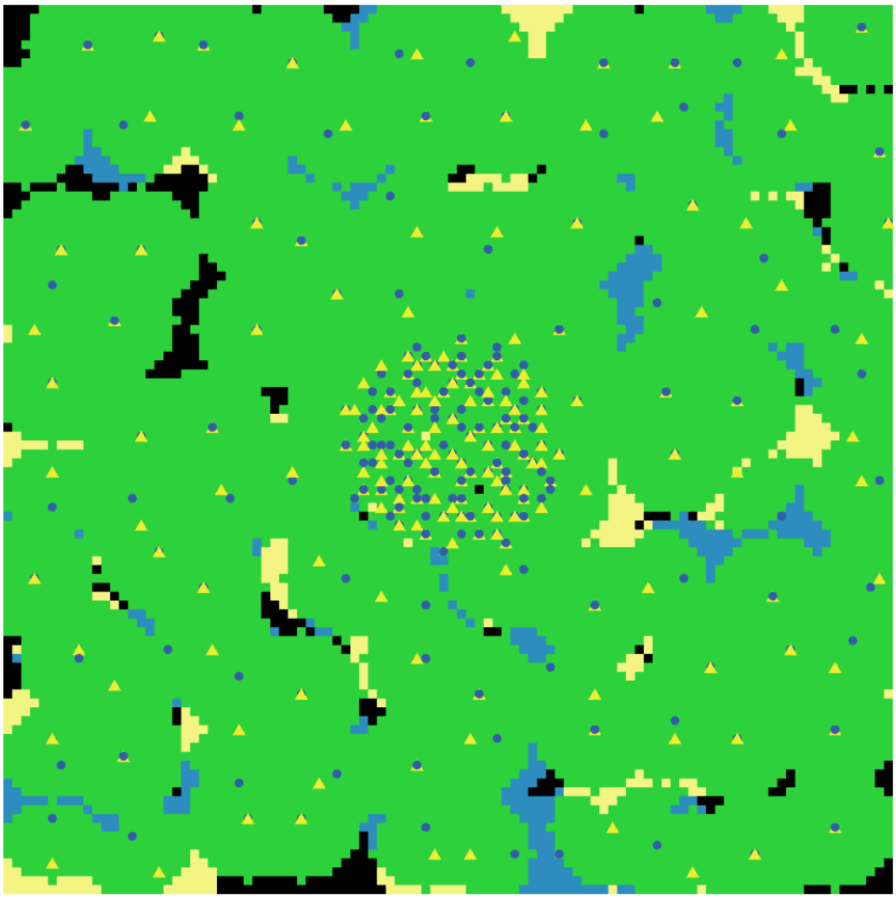

Figure 2: Base station allocation and coverage areas. The central area with a more dense distribution of base stations represents a city centre. One operator is blue and second operator is yellow. Green areas have coverage of both operators and black areas have no coverage.

5.1.2 Agent Attributes

Every individual agent belongs to an agent class. This model has two classes, one for mobile users and one for base stations. A class has a set of class variables, or attributes, and here we discuss the most important of them. Some attributes are implicitly mentioned in the next section where agent behavior is explained.

First of all, users know their home and work coordinates. Secondly, each user has attributes for the time when he leaves home to go to work, how long he stays at work and the time when he leaves work to go back home. The time to leave home is taken from a normal distribution with the mean at 08:00 AM and a standard deviation of 20 minutes, which means that about 99.7% of users leave home between 07:00 AM and 09:00 AM (see Preston (2016) for an explanation of the 68-95-99.7 Rule). In a similar way, the user stays at the work location for a random working time that is normally distributed with a mean of 8 hours and a standard distribution of 20 minutes. After the working time has passed, the user leaves work to go home. Finally, the user has an attribute that determines which networks the user is allowed to connect to, representing a mobile subscription. This attribute is used when the user is searching for nearby base stations.

Base station agents have attributes for the location coordinates of the BS and for the type of base station, i.e., whether the BS is in the central area or outside the central area. An operator attribute specifies to which MNO the BS belongs to. Each base station has a radius and a list of tiles that fall inside its coverage. In addition, a base station has a fixed number of radio resource blocks at its disposal.

5.1.3 Agent Behavior

The actions of mobile user agents consist of movement, scanning for base stations, base station selection, session handling and possible speed and resource block requirement calculation. Then the base station agents serve connected users by allocating radio resources to them. During a simulation run, a user agent starts in his home location, moves to his work location, stays at work and finally returns back home.

Movement, Base Station Selection and Session Handling

Users move along a straight path between the home and work locations, with a speed of 250 m/min = 15 km/h. At every time step (called tick), after moving, a user scans for possible base station candidates, selects a base station with the strongest signal, and connects to it. The connection is visible in the runtime environment as an arrow between the user and the base station. If a user does not move during a tick, it does not search for base stations but stays connected to the BS it (possibly) was connected to in the previous tick. This is to prevent unnecessary BS switching if there are multiple base stations within equal distance from the user.

The strongest signal is determined based on the distance to the base station normalized with the range of the base station, since the model includes base stations with two different ranges. To explain this, let's consider a case where a user is in a location with two overlapping cells, where base station A has a range of 2 km and base station B has a range of 500 m. If the user is 1 km away from A and 500 m away from B, the user will choose A even though B is closer. This is because the normalized distances are $dist_A$ = 1 km / 2 km = 0.5 and $dist_B$ = 0.5 km / 0.5 km = 1.

Network usage by users is divided into sessions. This means that users only consume data for certain periods of time, not constantly. If a user is not in session, a session starts with 20 % probability. Similarly, if a user is in a session, the session ends with 20 % probability. These probabilities result in users having sessions roughly half of the time. Here the term session does not refer to a data connection, but to a willingness to use the network. As a result, a user might be in a session even if there is no network available. In fact, a session just means that a user has a non-zero speed requirement; if not in a session, the speed requirement is zero.

Speed Requirement and Resource Block Calculation

If the user is in a session, next the required speed is calculated. Data usage is simplified to concern only the download speeds. Hence, upload speeds are not examined in this study, and in this section, *speed* refers to download speed. Data speeds are measured in units of megabits per second (Mbit/s). A more detailed definition of speed – e.g., whether it is the throughput or goodput – is considered irrelevant for the purposes of this study. Thus, the general term speed is used.

The speed requirement of a user varies between 1 and 20 Mbit/s, and it is calculated with the following formula:

$$reqSpeed = \exp(\ln(a) \ + \ \mathrm{rand}[0,1] \ \cdot \ (\ln(b) \ - \ \ln(a))),$$

where *reqSpeed* is the download speed required by the user, $a = 1$, $b = 20$ and rand[0,1] is a random number in range [0,1]. The calculation for the required speed is repeated once every tick when user is in a session, i.e., once per minute. Figure 3 shows the cumulative distribution function of the user speed demand.

Subsequently, it is calculated how many resource blocks the user needs to satisfy his speed requirement. One base station has 100 resource blocks, which are allocated to the connected users. The amount of resource blocks required to receive 1 Mbit/s speed depends on the distance between the user and the base station. Closest to the base station, one resource block is needed to get a speed of 1 Mbit/s, and furthest from the base station, i.e., on the cell edge, ten blocks are needed to get 1 Mbit/s. The needed resource blocks are calculated with the following formula:

$$reqBlocks = \Big\lceil \lceil \exp\Big[\frac{\ln(10)}{9} \cdot \Big((\frac{dist}{range}) \cdot 10 - 1\Big)\Big] \rceil \cdot reqSpeed \Big\rceil,$$

where *reqBlocks* is the number of resource blocks required by the user, *dist* is the distance from user to base station and *range* is the cell radius. Note the use of the ceiling function, $\lceil\ \rceil$, which rounds a number up to the closest integer. The amount of resource blocks for different distances between the user and base station are plotted in Figure 4.

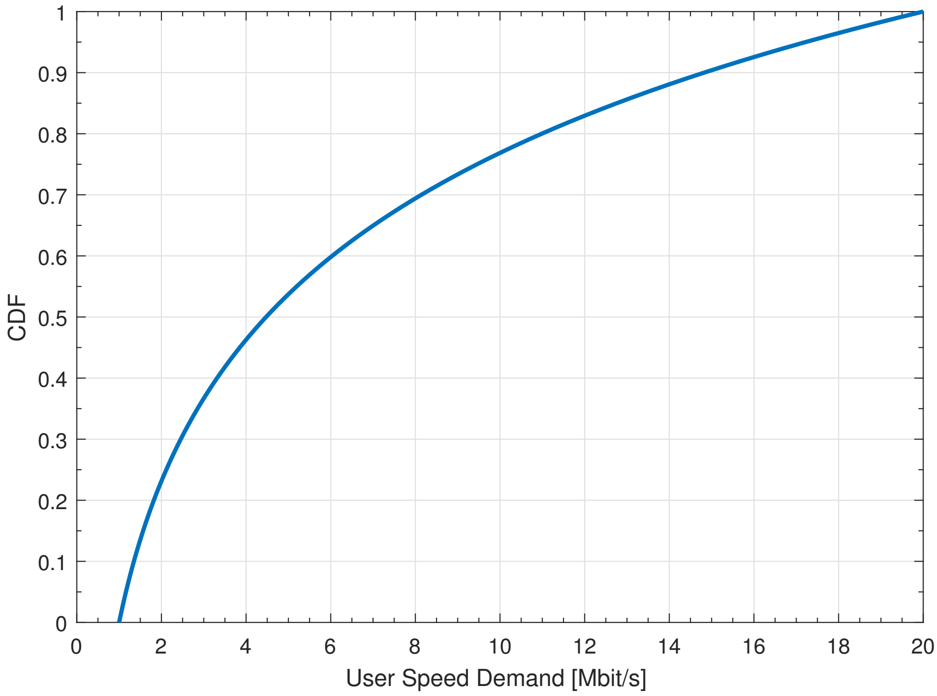

Figure 3: Cumulative distribution function for the user speed demand distribution. The CDF is $f(x) = \frac{\ln(x)}{\ln(a \cdot (\frac{b}{a}))}$, where $a = 1$, $b = 20$ and $x =$ user speed demand in Mbit/s.

Serving Users

After users are finished with their actions, the base stations serve them. A base station distributes its 100 radio resource blocks evenly among the connected users who are in a data session. If some users were allocated more than they requested, the excess is added back to the available resource blocks. If some users were allocated less blocks than they require, the possibly available blocks are redistributed evenly among these users. This is repeated until all users receive what they requested or the base station runs out of resource blocks. In case there are more users than there are resource blocks, the blocks are distributed one block at a time to the users in a random order.

The concept of a user requiring a certain speed and a certain number of resources is a bit vague. Probably most users in reality do not request a certain download speed when they are using data services; they just use them, and see how fast the connection is. Nevertheless, for the purposes of this simulation, it was decided to use this method, where users want a certain speed. Different speed requirements can be thought of as utilizing different services. For example, email, instant messaging, web browsing and video streaming all require different levels of throughput to function. In addition, note that the explained algorithm will never provide more resource blocks than a user requires. It is another interesting point of discussion whether this is

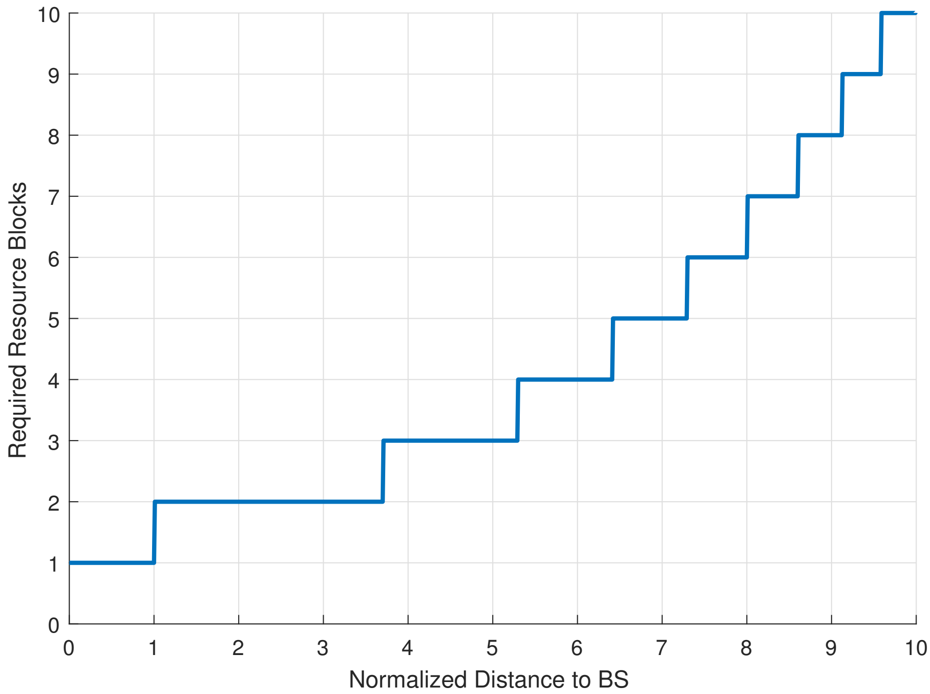

Figure 4: Resource block allocation as a function of distance to base station. Radius of the base station is scaled to be 10 units and the distance between user and BS is normalized to be in range 0-10.

realistic, but it was simply designed this way because of how the user satisfaction is calculated (see section 5.1.5). It is assumed that receiving higher speeds than required would still result in the same satisfaction as receiving what the user wants. Therefore, the algorithm is simplified to not allocate more blocks than required.

5.1.4 Time in the Simulation

The simulation advances in discrete time steps called ticks. A tick is modeled to represent one minute of time. One simulation run lasts for 780 ticks, which corresponds to 13 hours. These hours take place between 07:00 in the morning and 20:00 in the evening. Thirteen hours was decided because after this time every user has returned back home from work, and the idea of the model is to examine the data usage during the workday. A tick consist of three parts. First, the mobile users do their actions, then the base stations allocate resources, and finally the satisfaction score is calculated for each user depending on the required and served throughputs.

The original plan was for one run to take at least 30 days since it is the normal interval when users receive the subscription invoice and possibly change their subscription. If adaptive behavior would be implemented in the model, one run could last several months, and users could update their subscriptions each month. However, the longer the simulation run lasts, the more time it takes in real life because of limited computing power. Furthermore, longer simulation runs produce larger data files, which are slower to analyze with statistical software. Thus, it was decided to make the runs shorter. One workday was found to be a suitable time, and 13 hours was decided because in this time every user has time to go to work and back home.

5.1.5 Parameters of Interest

There are two parameters of the model that are varied between simulations. The first parameter is the users' ability to use either their own network only or both networks. The second parameter is the percentage of base station locations that have co-located base stations of the two MNOs. The objective is to investigate how varying these parameters affects the distribution of the users' scores. Thus, in modeling terms, the BS location sharing percentage and the network access mode of users are exogenous variables, whereas user satisfaction score is an endogenous variable.

The satisfaction score is calculated every tick for each user currently having a data session. The score is computed with the following formula:

$$\text{Score} = 5 + a \cdot \log\left(\frac{\text{Served Bit Rate}}{\text{Demanded Bit Rate}}\right), \qquad \text{Score} \in [0, 5],$$

where a is a constant parameter set to $a = 4$. Figure 5 visualizes the scoring function.

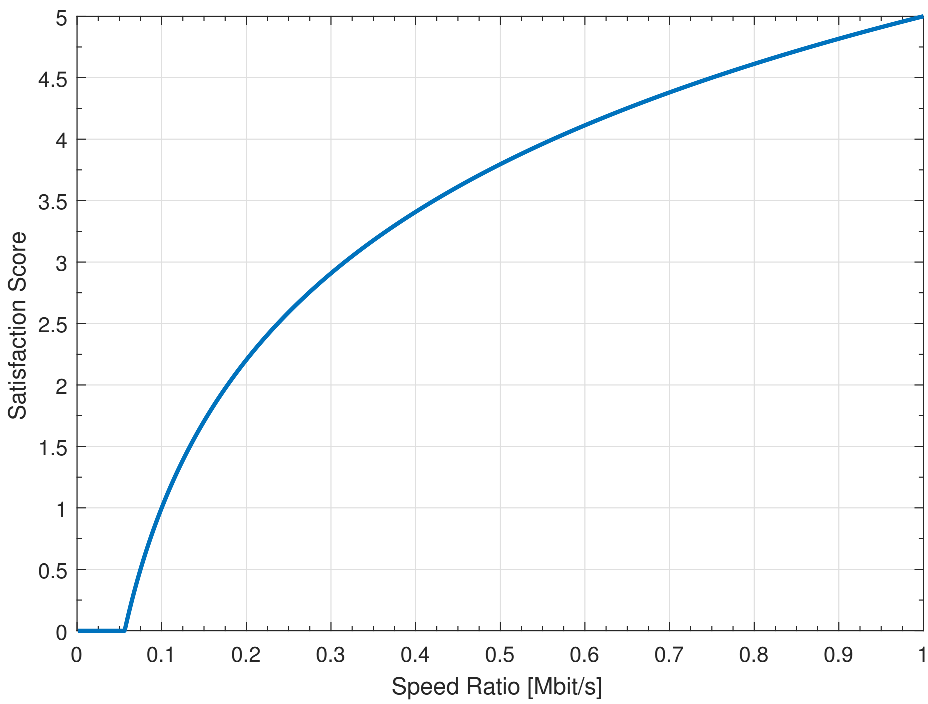

Figure 5: User satisfaction score as a function of the bit rate ratio. Speed Ratio = (Served Bit Rate / Demanded Bit Rate).

The relation of bit rate ratio and satisfaction score should not be linear, and the key idea in this function is that with lower bit rate ratios the satisfaction drops faster.

For example, when watching a video stream, a problem in playback, such as the picture freezing, lowers the satisfaction more than a drop in the video quality from high definition to standard definition, even if the change in served bit rate would be the same in these two cases. The score is directly attained from the QoS parameters of demanded bit rate and served bit rate. The above function is one "educated guess" of mapping the QoS parameters to user satisfaction, and it is possible to develop the function further in future studies.

The behavior of users is affected by a network usage parameter. When single access is used, the users only connect to the base stations of their own operator. With dual access in place, the users see the base stations of both operators equally available, and they choose the BS with the strongest signal, based on distance. If two base stations of different operators are equidistant from the user, e.g, if they are co-located, the user randomly connects to one of them.

5.2 Simulation Scenarios

After the system of mobile users, base stations and their environment has been modeled, it is time to run the operation of the model over time. This is called simulation. Between simulation runs, parameters are varied, which generates alternative simulation scenarios. The results of each scenario can then be compared.

For analysis in this thesis, a total of ten simulation scenarios were executed. The amount of colocated base stations was set to be 0, 25, 50, 75 and 100 percent of the total number of base stations. Each of these settings was run twice: first, with users only able to connect to one network, and second, with users able to connect to both networks. Table 3 lists the varied scenario parameters. Figure 6 shows the environment with different BS sharing percentages.

Table 3: Scenario parameters.

	Network usage	
	Single	Dual
BS Location Sharing %	0	0
	25	25
	50	50
	75	75
	100	100

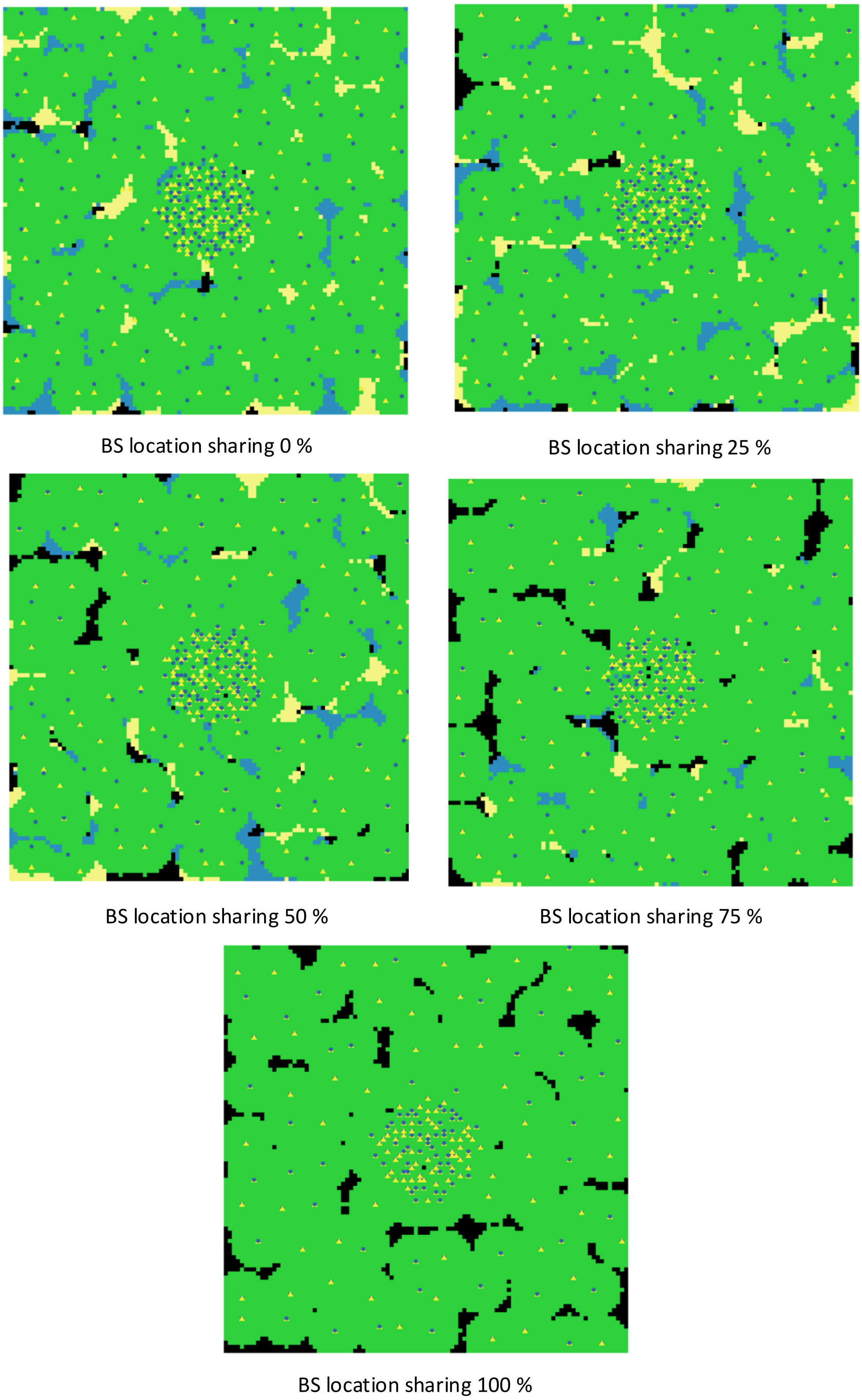

Figure 6: Runtime environments in different simulation scenarios.

5.3 Modeling Tool

The model and simulation were developed with Repast Simphony 2.3, an agent-based modeling and simulation toolbox and platform based on Java. The model code was written in ReLogo, a language specific to the ABM domain, which is incorporated in Repast Simphony. The ReLogo language is built on top of the Groovy language, which is integrated with Java and runs in a Java Virtual Machine. ReLogo, Groovy and most of Java code can be mixed however the modeler likes, which supports both beginners and more advanced modelers (Ozik et al., 2013). Any Groovy or Java external libraries can be imported by the programmer. The Repast Simphony toolbox was used with the Eclipse IDE (Integrated Development Environment).

ReLogo is based on the Logo family of modeling languages, which includes languages such as Logo, StarLogo and NetLogo. Since ReLogo is an ABM domain specific language, ReLogo comes with some pre-existing methods called primitives that help in creating agent-based models. ReLogo has a graphical runtime environment, that helps visualize the progress of the simulation's virtual world. The runtime environment is customizable through code with radio buttons, sliders and monitors. File sinks for simulation outputs are also easy to create with the graphical user interface of the runtime environment.

Besides Repast, there are a number of ABM tools, such as StarLogo, NetLogo, MASON and Swarm. ABM applications can also be created with programming languages, including C++ or Java, computational mathematics systems, such as Matlab or Mathematica, or with spreadsheet macros, such as Excel Visual Basic for Applications (Macal and North, 2009). Repast was chosen because it is free and a colleague in the same research group had used it previously.

5.4 Remarks on Model Development

Developing the model was a challenging task since the modeler had no previous modeling experience. Several ideas for the simulation were considered. First, the idea was to compare different pricing schemes for the end-user multihoming and national roaming market mechanisms. Users would consume mobile data with a certain pricing scheme and they could dynamically switch their data plan or operator, or they could start using multihoming or national roaming as an extra service, with a certain price. After some time it was realized that before pricing could be modeled, all the ground work had to be done regarding the data consumption of users. The ambitious plans had to be reduced quite a bit to keep the work load within the scope of a thesis. In the end, comparing national roaming and multihoming with simulation was excluded, and the model was focused on flexible access in general.

6 Analysis

The results of the study are presented in this section. Data on the satisfaction of mobile users was gathered for each of the ten simulation scenarios. The satisfaction score for each user was collected for each tick of the simulation. The model had 10 000 users and ran for 780 ticks, which results in 7.8 million data points per run. After removing the data points where users are not in a data session, roughly half of the data points remained. Thus, on average the users were in a data session during half of their time. The satisfaction scores of users in a session were then analyzed and visualized with R statistical software.

Figures 7 to 11 show the distribution of scores with different sharing levels of base station locations. Each figure has two distributions, one for the single network usage case and one for the dual case. The bin width of the histograms is 0.25: the first bars include scores in range [0,0.25), the second in range [0.25,0.5), and so forth. The density on the y-axis is calculated with the formula:

$$Density = \frac{f_i}{n \cdot b},$$

where f_i is the frequency of scores in bin i, n is the number of scores in total and b is the bin width. The total area of all the rectangles in the histogram equals 1.

Figure 7 shows that with 100 % base station location sharing, the satisfaction distributions are (nearly) identical in both the single and dual case. Since the base stations of the two MNOs share the same locations, the coverage areas are identical. Furthermore, in the dual access case, all users can use both networks. Thus, the network load is similarly distributed as in the single access case.

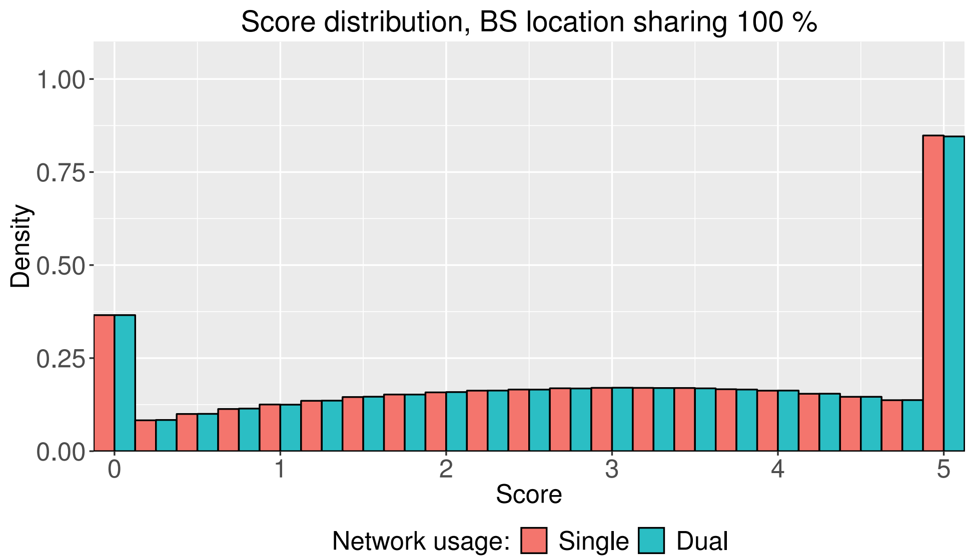

Figure 7: Distribution of user satisfaction with 100 % shared BS locations.

It can be seen from the distributions that when the amount of base station location sharing decreases, using two networks results in higher scores. In Figure 11, the amount of scores in the leftmost bin (with scores in range [0,0.25[) is one third less with dual access. The difference in the lowest scores is most probably due to coverage differences. In an area of partial coverage, where a user has no coverage in the single access case, the satisfaction score is zero. In contrast, with dual access, the user can have normal coverage, resulting in a non-zero score, which will vary depending on congestion.

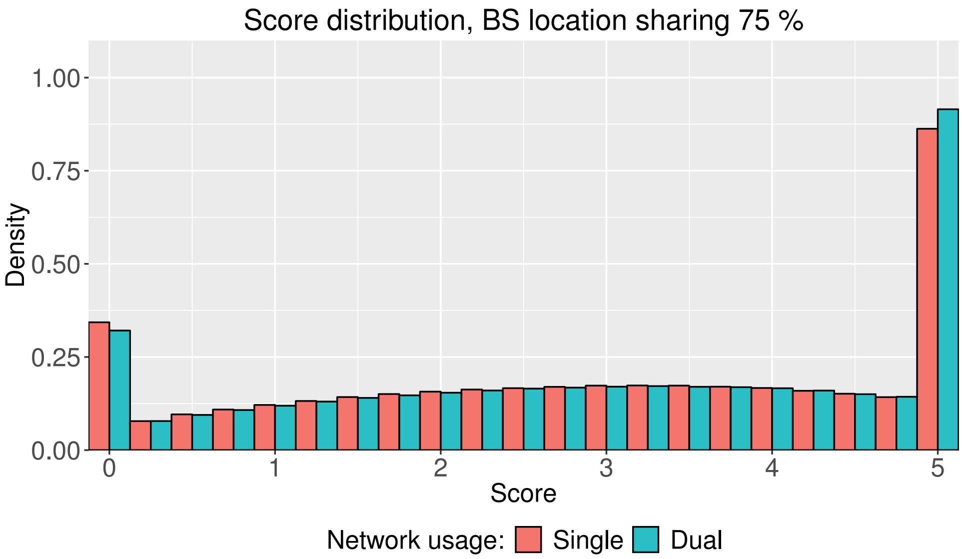

Figure 8: Distribution of user satisfaction with 75 % shared BS locations.

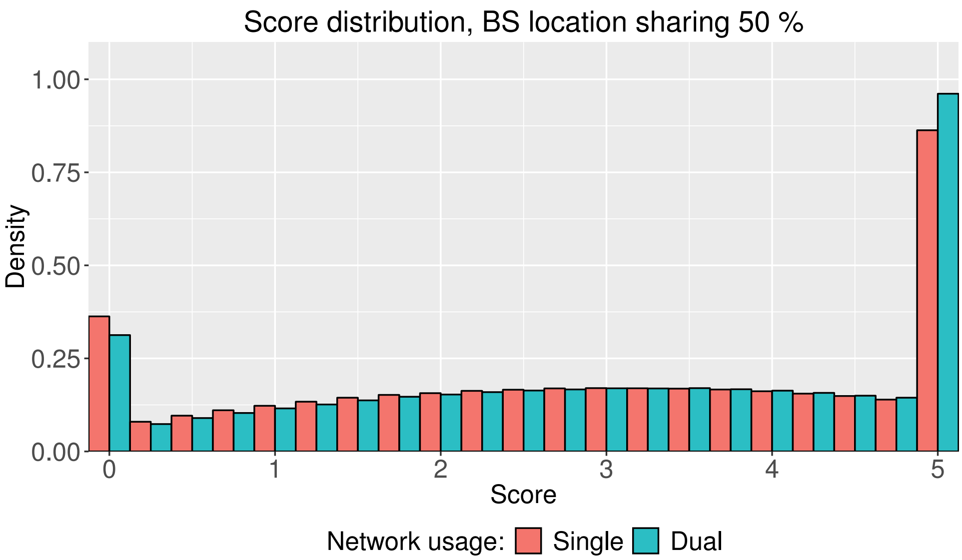

Figure 9: Distribution of user satisfaction with 50 % shared BS locations.

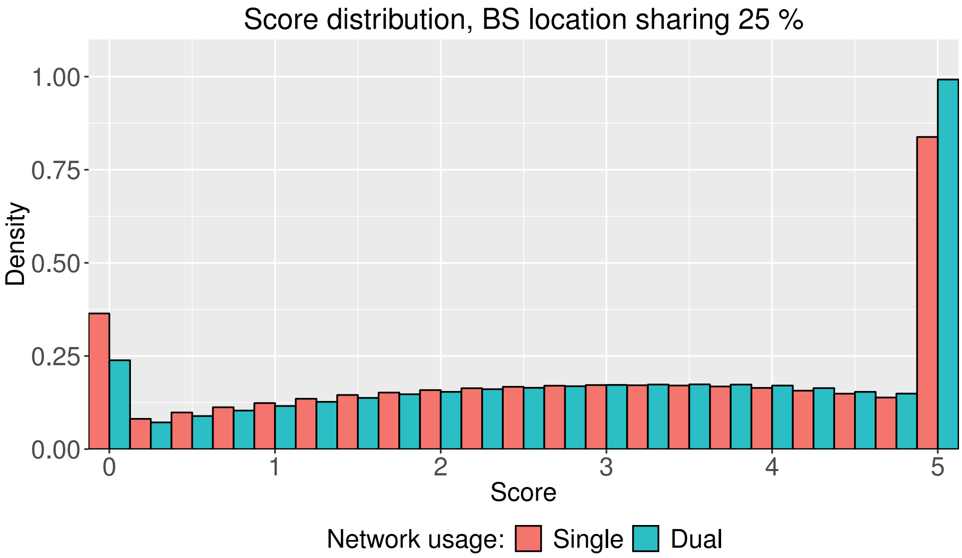

Figure 10: Distribution of user satisfaction with 25 % shared BS locations.

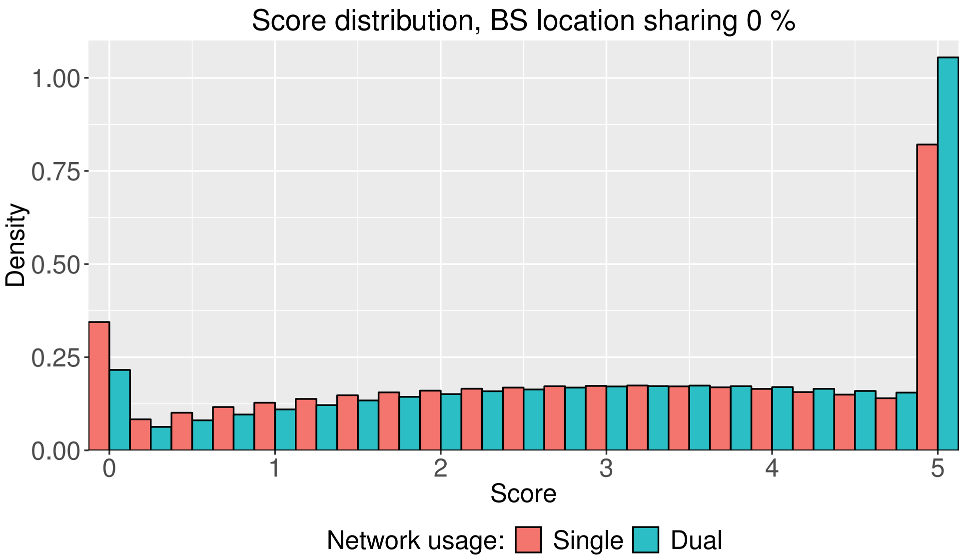

Figure 11: Distribution of user satisfaction with 0 % shared BS locations.

Table 4 shows the mean and median values for the ten different simulation runs. Comparing these values between the single and dual access cases shows the same trend that can be seen by examining the distribution graphs: increasing the base station location sharing percentage decreases the difference in user satisfaction scores between single and dual access. With zero percent location sharing, the mean score for dual access is 10 % higher compared to single access, and the median is 13 % higher. When three-fourths of base stations are in the same locations, the mean for the dual access case is only 1.6 % higher than the mean for single access, and the median is 2.1 % higher. With 100 % BS location sharing, there is no benefit from using two networks, which is reasonable coverage-wise, since the two networks have equivalent coverage areas. These results are in line with the fact that the coverage disparity between two networks decreases when the base stations are more co-located.

With all the base stations of the two networks in the same locations, the mean and median of satisfaction are, in fact, slightly lower in the dual access case. This is probably due to different levels of congestion in the two cases. With single access, half of the users use the first MNO's base stations and the other half use the second MNO's base stations. However, with dual access, the users decide randomly which MNO's base stations to connect to. The decisions are distributed uniformly, which results in roughly even usage of the two MNOs' base stations, but during the run, individual base stations could be more congested in the dual access case, resulting in lower satisfaction scores. For the same reason, the distributions in Figure 7 are not exactly identical.

Table 4: Statistics of Scores. Share (%) is the amount of BSs in shared locations, Mean(s) and Mean(d) are the means of scores in the single and dual cases, respectively, and Diff(%) is the difference between the means. The notation is the same for the medians.

Share (%)	Mean(s)	Mean(d)	Diff (%)	Median(s)	Median(d)	Diff (%)
0	2.91	3.20	10.2	3.05	3.45	13.1
25	2.91	3.13	7.4	3.06	3.34	9.1
50	2.93	3.04	4.0	3.09	3.25	5.2
75	2.95	3.00	1.6	3.12	3.19	2.1
100	2.91	2.90	-0.1	3.06	3.05	-0.2

These results support the notion that using multiple mobile networks can improve the mobile service. When networks have coverage disparities, users can benefit in terms of availability. Nevertheless, if no operator has coverage in a certain area, flexible access gives no benefits.

7 Discussion

The agent-based simulations showed that user benefit from using multiple networks increases when the coverage disparity between operators increases. The coverage disparity was altered by changing the number of shared base station locations. When the coverage of two networks is equal – and all base stations are in shared locations – switching between them offers no benefits in availability. With no base stations in shared locations, the mean satisfaction score increased by 10 %, from 2.91, when using a single network, to 3.20, when using two networks. These quantitative results cannot be generalized, but they offer valuable insight by suggesting that user satisfaction can be increased by using multiple networks.

The most relevant differences in satisfaction are with the lowest scores. The lowest score of zero means that the user has no network availability. One could think that having any network is better than having no network. This is at least the case with phone calls: users are very annoyed if the phone has no signal. With data services, one can also think that having no service could, in fact, be better than an extremely poor service. For example, a user might be frustrated for wasting time waiting for a slow service, and hope he would not have even begun using it.

It is important to note that with multiple networks, the satisfaction of users can also decrease, due to capacity constraints. If users of an operator with no coverage in an area of partial coverage gain access to a competitor's base station, the BS will have to distribute its capacity to more users. Thus, the QoS of the earlier users of the BS can decrease. Coverage and capacity where not examined separately in the simulation. Thus, it was not possible to determine how large a proportion of the changes in satisfaction where due to changes in coverage and what due to changes in traffic volume.

Benefit of using multiple networks was studied in general, because due to time and resource constraints, implementing and comparing national roaming and multihoming was excluded from the model. However, the present model could be seen as an example of multihoming with selection of best operator based on signal strength. Some of the original ideas also included adding retail pricing to the model, and modeling customer willingness to pay, but they have to be left for future work.

The studied literature and expert interviews gave general knowledge on usage of multiple networks, and specifically on national roaming and end-user multihoming. They explained that using multiple networks can benefit users in terms of coverage and capacity. However, there are many factors which complicate the matter.

National roaming was generally opposed as a mechanism to improve the availability of networks. This is probably due to the historical failures of implementing NR, and the many risks that NR is perceived to introduce to the market. The main argument against NR is that it can decrease infrastructure investments and slow down the development of mobile networks. Still, there are ways to implement NR in a controlled and restricted manner, that could benefit end-users with less risks to the market, but it is doubtful that NR will be introduced to the whole population of a country, anywhere and anytime. NR could be implemented only as a regional service, in areas with major coverage disparities, such as the archipelago. Another way could be to offer roaming as an optional extra service that could be used by consumers who have need for it. However, if this service should be profitable to operators, it might lead the retail price of the service to be too high for most consumers. Of course, regulatory authorities could impose upper limits for the wholesale or retail prices, but operators might not be willing to make NR agreements if they do not see enough benefit in them.

Coverage disparities enable operators to compete in coverage, which is the normal way how operators try to differentiate from their rivals. If multiple networks are available to the users, this coverage competition can disappear. However, in countries such as Finland, where the coverage is already good and data usage is high, focus of competition has turned towards data speeds. End-user multihoming could further increase this competition, if users could dynamically select the fastest network. National roaming can help users suffering from lack of network availability, but it will not bring faster speeds to those users who already have coverage.

7.1 Method Feasibility

Agent-based modeling proved to be a suitable method for studying mobile user behavior in general. It is natural to depict mobile users as agents and rather straightforward to define attributes for users and base stations. Especially when combined with a geographical environment, ABM is convenient for studying mobility. Furthermore, the toolbox allows the creation of more realistic environments with three dimensions: one could model the map of a real city with buildings and geographical elements such as hills. The Repast modeling toolbox was found to be relatively easy to learn, especially with the ReLogo modeling language. Repast Simphony with Relogo is definitely the choice for beginners with less programming background. For advanced programmers and for more computing intensive simulations, the toolbox has a version called Repast for High Performance Computing, where models are written in C++ programming language. However, the time and resources required to create more complex models should be proportioned with the research goals and the value acquired from the efforts of complexifying the model. ABM provides the opportunity for a wide range of simulations, but it is up to the researcher to determine if simulation is the right approach in the first place. ABM can be time consuming and it can be fun. However, the modeler can get side-tracked and carried away from the research question and what he is in fact pursuing.

Even though agent-based modeling and simulation aims to reveal emergent phenomena, there is a possibility that the modeler might, in fact, know the output of the simulation. This is due to the modeler having so much control over the modeling. Like in any programming, ABM easily leads to a process where the model is iteratively developed, run, analyzed, tweaked and run again. This might not be a fault, per se, and it is fine for modeling to be an iterative process, but emergent and unforeseen results might not be produced when the modeler is controlling the whole process. However, with more complexity, for example in the form of creating adapting and learning agents, emergent phenomena is more likely to occur. Still, the modeler may have a pre-existing idea of what the simulation outputs will be like –

or more dangerously, what they should be like–, and there is an ethical risk that the simulation is tweaked to produce what the modeler wants. Moreover, the modeler may become blind to his own creation. Thus, simulation models should be produced collaboratively and held subject to transparent review by peers along the process.

7.2 Model Assessment

It is easier to create a model than to assess it. The model constructed in this thesis lacks proper verification and validation. Thus, there are many aspects of the model which would probably be modified after more careful assessment. The modeler has verified that the program code does what it is meant to do. Reliability has been tested informally by re-running the simulations. However, no software exists without programming errors. Furthermore, even if the modeler has correctly implemented what he wanted to implement, it does not assure that the modeler is implementing the right matters. All models are wrong, but a modeler should try to evaluate just how wrong the model is. It is important to assess the assumptions of the model. Are the inputs reasonable and realistic? What affects the outcomes? This is of course a continuous process that never ends, but here are some current thoughts.

Most of the assumptions regard user behavior. The user model has intentional simplifications in place for the movement of users. They travel at a constant speed along straight lines, which is not realistic, but is a reasonable simplification. The users' homes are distributed uniformly, whereas in real world they would be concentrated on specific residential areas. The model for data sessions resulted in users spending half of their time having data sessions, which seems to be a too high amount. Since the users spend most of their simulation time at work, it is unrealistic that they would be using data services so abundantly. Thus, modeling the sessions should be re-thought in the future.

Base station locations affect the results, because they determine the network coverages. The base stations were allocated to areas with regular intervals, but with local randomness. This randomness complicated the control over how high coverage operators have in each scenario. Between the five cases of BS location sharing from 0 % to 100 %, the BS locations change randomly in the local areas, and not only due to the different percentages of location sharing. Currently, it is not certain to what extent the satisfaction score results are due to the variation of the BS location sharing parameter and to what extent due to this basic local randomness. For instance, a non-random lattice structure of base stations would ease the comparison of coverage areas between scenarios. A lattice would look simple and unrealistic, but one can also question how realistic the locally random allocation is. In reality, MNOs surely determine and optimize BS locations carefully. The simulation platform has code in place to output the details of operators' coverage percentages. The coverages should be more rigorously measured and compared in the future to improve credibility.

One could easily want to try out every possible idea by simulating as many scenarios as possible. However, research was focused on a solid understanding of ABM and on making a platform that is a basis for future research. Thus, the ten simulated scenarios are more of an example of what is possible with the platform.

7.3 Simulation Platform and Future Prospects

As a result of the ABM process, software was created that acts as a platform for future modeling. The platform can be used and the current model can be easily modified to study various phenomena. Different environments and mobile usage scenarios can be studied by building on top of the existing code. There are many possibilities for base station layouts and thus for coverage and capacity modeling. The user movement patterns are easily modified – the commuter model is only one prototype model. It would be interesting to model other mobility use cases. For instance, in Finland, it is a common free time practice to travel long distances from urban areas to summer cottages. En route and at the destination, users experience issues in availability and capacity. Contrary to the showcased commuter model with ten thousand users, the journey of a single car with a family of four people could be modeled, while they travel from city to countryside, and their availability could be compared with single or multi-access.

The current model studied using multiple networks in general, and the network selection presented could be considered an example of multihoming if desired. The next step in developing the model could be to implement distinct scenarios for the network selection in the cases of national roaming and multihoming. Firstly, the NR mechanism, users should only connect to another network when they have no coverage of the home network. For example emergency scenarios could then be investigated by introducing network blackouts and studying how the user satisfaction changes when users start roaming. Secondly, dynamic interface selection in the case of multihoming could be implemented so that the faster network is selected by comparing the capacities in the available networks. Only the downlink speeds were modeled in this thesis, but in reality, uplink QoS is increasingly relevant since users upload more and more online content and even send live video streams from their devices. Thus, a next version of the platform could incorporate also the upload functionality. If the concept of speed needed to be modeled more accurately, the platform could separate between the throughput and goodput of the network. Furthermore, the need for measuring user satisfaction needs to be reconsidered. Currently, satisfaction is derived from the speed parameters. It would be possible to concentrate only these QoS parameters and to exclude the computation of satisfaction. This would, of course, change the focus of research to be more technical. In any case, if user satisfaction is kept in the model, the function should be reviewed and developed further.

What is yet lacking from the current user model is the users' ability to learn and to adapt their behavior. The next stage in development would be to have users make decisions based on the knowledge of their historical satisfaction with the mobile service. Subscription pricing could be added to the model and to the decision-making process, and a simulation run could last for several months. As a result, a user could decide for example at the end of each month if he wants to switch or keep the current operator, based on his historical experience and the present price offerings.

8 Conclusion

This Master's Thesis studied how mobile users could benefit from flexible access. The scope of using multiple networks was narrowed down to examining a user-driven approach, end-user multihoming, and an operator-driven approach, national roaming. The two approaches were studied by reviewing literature and by performing five expert interviews. The main method used in this study was agent-based modeling (ABM). The feasibility of ABM in evaluating the benefits of flexible access was studied, and a computer simulation model was created to study how much user satisfaction increases with flexible access. This section summarizes the main findings of the study, assesses them, and gives recommendations for future research.

8.1 Key findings

The simulation model suggests that the satisfaction of mobile users increases by using more than one mobile network, when the coverage disparity between networks increases. ABM was found to be feasible method to research mobile user behavior and satisfaction. It is useful for creating various base station topologies and mobile service use cases. However, building credible agent-based models requires considerable time and effort. The created simulation model code can be used as a platform for future studies.

The background literature review and interviews provided insight into the use of multiple mobile networks in the scope of national roaming and end-user multihoming. National roaming was found to have many drawbacks including decreasing the level of competition in the operator market. Therefore, national roaming faces opposition and by many is not considered a good approach to using multiple networks. However, it was found that national roaming could be implemented with certain spatial, temporal, regulatory and monetary restrictions. End-user multihoming is technically possible, and could enable dynamic interface selection where users can connect to the network which offers a better service by some metrics, such as throughput or price.

Both mechanisms can benefit users by improving the service availability and resilience, and end-user multihoming can also improve throughput. The implementation and diffusion of either mechanism into everyday use depends on many stakeholders, such as device manufacturers, operators, regulators and end users. For either of the mechanisms of flexible access to be adopted, the coverage disparity or differences in technology between operators have to be high enough: when users are dissatisfied with single access, they can benefit from flexible access.

8.2 Results Assessment

The results of a simulation are always the result of the assumptions made by the modeler. The results obtained in the simulation of this thesis are the output of the assumptions explained in Section 5, and cannot be generalized. The programming code has only been verified by the modeler himself, but debugging has not been conducted by anyone else. The assumption on user sessions resulted in users spending half of their time using data, which should be corrected to be more realistic. The model for the allocation of base stations included local randomness which complicated the interpretation of the results and obscured what caused the coverage differences between scenarios.

Despite the shortcomings, the simulation results give insight about the benefits of using multiple networks. However, proper verification and validation would need to be conducted for the results to be quantitatively relevant. A face validation by peers could make the model more credible, and the results should be compared with results from other studies.

The interviewed experts gave quite similar answers, which may suggest that there was not enough variation between interviewees. In addition, there were many questions that the respondents could not answer to. Thus, the questions could have been more rigorously devised, or the interviews could have been expanded to cover additional people of more various knowledge in the field.

8.3 Future Research

There is considerable scope for future studies. It would be interesting to add the mechanisms of national roaming and end-user multihoming into the agent-based model. The user benefits could then be compared between the two mechanims. Retail pricing models could be added with options for users to switch between operators. Multihoming and roaming could be modeled as extra services added to a primary subscription, which would be used only when in need of better coverage.

In future simulation scenarios, the user satisfaction could be compared by varying the number of users who employ a flexible access mechanism. It would be interesting to see what are the effects first with a small number of flexible access users and then gradually increase the number to a situation where all users can connect to multiple networks. Future studies could also simulate what happens with flexible access when one operator's network suffers from an outage.

While this study had a user-centric approach, the point of view of mobile operators should be studied. For example, the wholesale pricing between operators in national roaming could be investigated. Operators could also be modeled to alter their base station locations and technologies during the simulation. The model in this study incorporated only two operators, whereas future models could contain three or more operators.

One of the key features of agent-based simulation, learning and adapting agents, were missing from this study. A future model could incorporate elements of machine learning, with users recognizing patterns and modifying their behavior based on their historical experience. The present model ran and compared distinct separate scenarios, and agents did not have any rules in place to modify their behavior. If users could choose their operator and access type, the simulation could result in interesting emergent behavior of agents, which is missing from this study.

For more realistic models, the agents could be laid over a map of an existing area, and the user movement patterns and base station locations could be modeled more realistically. Even a three-dimensional model could be implemented, for example to study indoor coverage inside buildings. While the simulations were ran on a standard desktop computer, running a more complex simulation for longer periods would require the employment of computing clusters. Moreover, a prototype could be made with the high-performance computing version of the simulation toolbox. However, a researcher must focus on the model core and avoid getting side-tracked by creating complex models just for the sake of complexity.

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Appendix A: Interview topics

#	Topic	Example question
1	Background of interviewee	Can you briefly talk about yourself and your role in your organization?
2	Using multiple mobile networks in general	Generally, is there a benefit for consumers of using multiple mobile networks? Do Finnish consumers have a need to use multiple mobile networks?
3	Briefing about the research topic	
4	End-user multihoming	How do you see the future development of end-user multihoming? What effects to the operator market and competition do you see of dynamic interface selection?
5	National roaming (NR)	Does NR differ technically from international roaming? What are the pros and cons of NR? How would NR affect the operator business?
6	Pricing of multi-access	What kind of pricing scheme would fit multihoming (or NR)? What do you think if NR would be an extra service subject to an extra price?